Technology of Tanks

I

Richard M Ogorkiewicz

JANE'S INFORMATION GROUP

Published in the United Kingdom in 1991 by
Jane's Information Group Limited
Sentinel House
163 Brighton Road
Coulsdon
Surrey CR5 2NX

ISBN 0-7106-0595-1

Distributed in the Philippines and the USA and its
dependencies by Jane's Information Group Inc.
1340 Braddock Place, Suite 300, PO Box 1436
Alexandria, Virginia 22313-2036

Printed and bound in the United Kingdom by Biddles Limited
Guildford and King's Lynn

Contents

8 Gun Control Systems

9 Guided Weapons

10 Mobility of Tanks

11 Tank Engines

12 Tank Transmissions

Preface

The object of this book is to provide a comprehensive account of the technology of tanks, the tracked armoured fighting vehicles which have become such an important element of military power.

The account is concerned primarily with the current state of tank technology. But it also covers preceding developments, to help the understanding of how, or why, tanks have taken their present form while other forms or concepts have been abandoned. It also includes an outline of the evolution of tanks from their inception, to put their current state in its historical perspective and in the process to throw additional light on their origins, about which there is still some confusion.

Although the book is meant to be comprehensive, it can not deal with every facet of the technology of tanks, as this is outside the scope of a single work. However, it seeks to cover all the principal aspects of the subject.

Such a treatment of the technology of tanks does not appear to have been attempted before but the case for it became increasingly evident to me in the course of my involvement with tanks, which made me aware of the need for a book of this kind on the part of engineers, army officers and many others.

My involvement with tanks has covered more than forty years. For a major part of this period I have acted as a consultant engineer to a number of industrial and government organisations concerned with the development of armoured vehicles, which has brought me into contact with many who have a direct interest in the technology of tanks. I have also met many more with similar interests as a result of giving lectures on armoured vehicles not only in Britain and the United States but also in other countries, including Brazil, China, Israel, Japan and Sweden, and, most recently, as a visiting professor at the Royal Military College of Science.

Some of the interest in tank technology can be satisfied by lectures like those I have been invited to give and by articles published in various journals, of which I have written about four hundred. The first of them appeared in 1949 in the *Royal Armoured Corps Journal* and has been followed by others not only in that journal but also in *Armor* and many others, including the *International Defense Review* of which I have become a consulting editor. However, articles as well as lectures can only deal with particular aspects of tank technology and while they have given me an opportunity to rehearse the presentation of some of it they can not answer the need for a book that deals with the whole subject.

I was encouraged to embark on the writing of a book that would meet this need by the reception accorded to my two earlier books which dealt with some aspects of tank technology in more general terms. They were *Armour* and *Design and Development of Fighting Vehicles*. Both of these were published in the United States as well as Britain; the first was also published in Italy as *I Corazzati* and republished in Britain as *Armoured Forces* while the second was also published in a Japanese translation. Both books have been out of print for some time but they have continued to be used as reference or text-books, which spurred me to produce another and more up-to-date as well as more comprehensive book.

During the course of my studies and writing I also received encouragement from many other quarters. In particular, my early studies benefited greatly from the encouragement and help given to me by my father, Colonel Marian A Ogorkiewicz, by Colonel Robert J Icks, in his day the leading US historian of armoured vehicles with whom I corresponded weekly for more than twenty years, and by Sir Basil Liddell Hart, whom I visited many times, especially when he was writing his two-volume history of the Royal Tank Regiment.

More recently I have benefited from discussions with several of the leaders in the field of tank development, who not only enabled me to examine and to operate the tanks with which they have been involved but who also became friends, now of many years standing. They include Sven Berge, the originator of the Swedish S-tank; Major General Israel Tal, who has directed the development of the Israeli Merkava tank; Iwao Hayashi, who led the team which designed Japan's Type 74 tank; and Jose Luiz Whitaker Ribeiro, the president of the Engesa Company.

Other friends who also helped me in my studies of armoured vehicles include Dr Philip W Lett, vice president of Chrysler and then of General Dynamics Land Systems, Leslie F Little, who was Vickers-Armstrongs' chief designer during the late 1930s and early 1940s, and Dr M G Bekker, who was responsible for much of the upsurge of interest in soil-vehicle mechanics during the 1960s.

I was also fortunate in being able to meet and correspond with some of the pioneers of tank development. They included Lieutenant Colonel Philip Johnson, who designed the British Medium D tank at the end of the First World War, and Lieutenant General Tomio Hara, who designed the first Japanese tank.

Some of those who helped and encouraged me in my studies have since passed away but I would like to record my gratitude to them as well as to all the others and I only wish that I could mention them all by name.

I would also like to record my thanks to all the industrial organisations and government departments which have supplied information over the years and which have provided the photographs that are reproduced in the book together with an individual acknowledgement of their origin.

London 1991 *Richard M Ogorkiewicz*

Chapter 1

Outline of the Evolution of Tanks to 1945

1.1 Origins of Tanks

Tanks are, in essence, mobile, protected weapon platforms. More specifically they are automotive, tracked, armoured carriers of heavy direct-fire weapons. As such, they stem from developments in two different fields. One is that of automotive vehicles and in particular of tracked tractors, which formed the basis of the construction of the first tanks as armoured vehicles capable of cross-country movement. The other is that of the development of heavy weapons, which had grown in importance in relation to individual, portable weapons but whose effectiveness was constrained by their limited mobility until it proved possible to overcome this by mounting them in tanks. In consequence, the automotive mobility and the armour protection with which tanks were endowed became a means of increasing the effectiveness of heavy, direct-fire weapons by making them more mobile and this has come to account for the lasting importance of tanks.

The first practical step in the development of self-propelled vehicles for military purposes was taken in 1769, when N J Cugnot, a French military engineer, built a steam-powered wheeled vehicle for towing guns (1.1). A year later R L Edgeworth took out a patent in Britain for a 'portable railway', which embodied the essence of a track. More detailed schemes for tracked running gear were put forward in patents taken during the second half of the 19th century (1.2). At the same time some steam traction engines were built in the United States with tracks instead of wheels by W P Miller in 1858, by T S Minnis in 1867 and by R C Parvin in 1873 (1.3). However, the development of tracked tractors did not begin in earnest until 1904, when B Holt replaced the rear wheels of one of the steam traction engines produced in California by his company by tracks. Because it retained its front wheels, Holt's original tracked tractor was, in effect, a half-track, as were the tractors built by his company between 1904 and 1912. In the meantime, in 1905, Richard Hornsby and Sons Ltd. built in Britain the first fully tracked tractor (1.4).

Well before this happened, in 1855, J Cowen took out patent No 747 in Britain for a steam-powered wheeled armoured vehicle armed with guns and in 1899 John Fowler & Co Ltd of Leeds actually built four steam-powered wheeled armoured vehicles for use by the British forces in the war in South Africa (1.5). The latter were only armoured road locomotives designed to tow armour-plated wagons and guns but nevertheless they were the first self-propelled armoured vehicles to be built.

The first vehicles to be armed also appeared in 1899. They consisted of some of the earliest motor vehicles which were fitted with machine guns with the object of increasing the mobility of the latter. One of them appeared in England and consisted of a powered quadricycle fitted by F R Simms with a Maxim machine gun (1.6). Another appeared soon afterwards in the United States and consisted of a three-wheeled car mounting a Colt machine gun built for Major R P Davidson.

What was bound to follow was a vehicle which was both armed and armoured. Such a vehicle was built, in fact, in 1902 in Britain, by F R Simms, under contract to the armament firm of Vickers, Sons and Maxim, Ltd (1.7). It failed to arouse the interest of British military authorities but a semi-armoured car exhibited in Paris in 1902 was tested in the following year by the French military authorities. The Russian authorities encouraged its builders, the Societé Charron, Girardot et Voigt, to develop a fully armoured car, which was completed by 1906. By then a second armoured car with a machine gun turret had also been built in Austria by the Austro-Daimler Company (1.8).

Little further progress was made with armoured cars until the outbreak of the First World War in 1914, when they began to be built and used in numbers. However, a few more attempts had been made by then to make guns more mobile by mounting them on unarmoured as well as armoured motor vehicles. This involved not only machine guns but also guns of up to 75mm, which were mounted on motor vehicles to provide mobile weapons against dirigible balloons and aircraft (1.9).

The mounting of guns on motor vehicles represented a considerable advance on earlier methods of moving weapons about, which relied on horse traction. However, the mobility of motor vehicles was confined almost entirely to roads and the effectiveness of the gun carriers as well as that of the armoured cars was consequently severely limited. The development of armoured cars was bound to be followed therefore by attempts to make them, or similar vehicles, capable of operating off the roads. The basis for this had already emerged in the form of the tracked running gear of tractors and its adoption for armoured cars or gun carriers would have provided the heavy weapons mounted in them with the cross-country mobility which they needed to be effective in most military operations.

However, tracked tractors were still a little known novelty and there was not much concern yet about the cross-country mobility of heavy weapons, which might have encouraged the mounting of them on tracked vehicles. In fact, it was not even generally recognised how important heavy weapons, and in particular field guns, had become in relation to the individual weapons on which armies continued to rely to a considerable extent. Their cross-country mobility and how it could be improved to allow them to be employed to the fullest extent were not, therefore, matters that exercised contemporary military thought.

Nevertheless, a few individuals had already conceived the idea of mounting heavy weapons on tracked armoured vehicles. Thus, as early as 1903 Captain Levavasseur of the French Artillery put forward a detailed proposal for a tracked armoured vehicle mounting a 75mm gun (1.10). Another proposal to mount a gun on a tracked chassis was made in 1908 by Major Donohue of the British Army Services Corps after he saw the original Hornsby tractor (1.11). In 1911 Captain G Burstyn of the Austro-Hungarian Army proposed a tracked armoured vehicle with a small calibre gun in a turret (1.12); in 1912 the British War Office received the design of another tracked armoured vehicle from an Australian engineer, L E de Mole. The design of yet another tracked armoured vehicle, which was to weigh

170 tons and carry a 120mm gun, was also started in 1911 by a Russian engineer, V D Mendeleev (1.13).

None of the proposals was put into effect but the idea of mounting guns on tracked armoured vehicles had obviously come into existence before the outbreak of the First World War, and so had the means of implementing it. In fact, it only required an armoured car to be combined with a tracked tractor to produce what was to be the tank. However, there was little incentive to do this until after the outbreak of the war, and when the first tanks were actually built they were not regarded as a means of making guns more mobile but as special purpose assault vehicles. What is more, this and other narrow concepts of tanks became widely accepted, to the detriment of their development and of their fullest, most effective use.

1.2 The First Tanks

Although the course of the First World War led to the production of tanks, its outbreak in August 1914 had no immediate impact on their development. The war was expected to be over quickly, won by much the same methods as before. However, after a time the opposing armies fought themselves to a standstill and, as their fire-power proved to be increasingly effective when deployed in defence, the traditional infantry attacks became increasingly more difficult. At the same time, the strength of defensive positions was increased further by the extensive use of entrenchments and barbed wire. The result, particularly on the Western Front in France, was deadlock, with neither side being able to break through the other's trench lines.

The problem which this situation was seen to pose in the light of the contemporary military practice was that of enabling the infantry to advance against enemy trenches in face of machine guns and barbed wire. In consequence, a number of people proposed the use of armoured assault vehicles, which would crush the barbed wire and whose protection would enable them to approach enemy trenches under machine gun fire. This implied special-purpose vehicles which, conceptually, bore a resemblance to ancient siege engines rather than the mobile weapon platforms that Levavasseur and Donohue had envisaged and which, in a restricted sense, the armoured cars already were.

In the longer term there was, however, another and much more fundamental problem to be resolved. It was the imbalance that had arisen between the offensive and defensive capabilities of armies. Thus they were able to make full use of their fire-power in static defence but not on the offensive, because of the difficulty of moving their heavy weapons about. This was the underlying cause of the stagnation of trench warfare rather than the difficulty the infantry had in attacking enemy trench lines. In fact, a way was eventually found for the infantry to attack entrenchments with the development, by the German Army, of infiltration tactics, which were used with considerable success in the initial stages of the German offensive in France in March 1918. But the advance of the infantry could not be backed by a corresponding movement forward of heavy weapons, when the latter still depended on horse traction or manhandling, and in the circumstances offensive action could not be sustained for any distance.

What was needed, therefore, was a general increase in the mobility of the heavy weapons, and in particular of the field guns, rather than a reincarnation of ancient siege vehicles. But this need was not perceived at the time, nor for some time afterwards, and tanks continued to be thought of in terms of special applications.

Thus, while the onset of trench warfare in 1914 accelerated the construction of the first tanks it also hindered the evolution of tanks as versatile, mobile instruments of warfare.

Who first came forward with the idea of using tracked armoured vehicles to solve the problem of attacking entrenchments, has been a matter of dispute. However, the idea had clearly emerged in Britain out of discussions held in October 1914 between Lt Colonel E D Swinton, who was the sole official war correspondent with the British Expeditionary Force in France, and Lt Colonel M Hankey, who held the influential position of Secretary of the Committee of Imperial Defence (1.14). Swinton subsequently claimed that he was the 'originator' of the tank (1.15). But, whatever ideas he might have had, he did not initiate the development of tanks in Britain (1.16).

The initiative in the development of British tanks came primarily from the officers of the Royal Naval Air Service and in particular of its Armoured Car Division, which was created to support naval aircraft deployed in France. Their experience with armoured cars led them to propose, from December 1914 onwards, more powerful vehicles capable of moving cross-country. An early proposal of theirs for a giant three-wheeler was not very practical but it inspired Winston S Churchill, the First Lord of the Admiralty, to set up a Landships Committee in February 1915 to explore the problem of cross-country armoured vehicles (1.17).

The formation of the Landships Committee under the chairmanship of E H Tennyson d'Eyncourt, the Director of Naval Construction, was followed by a

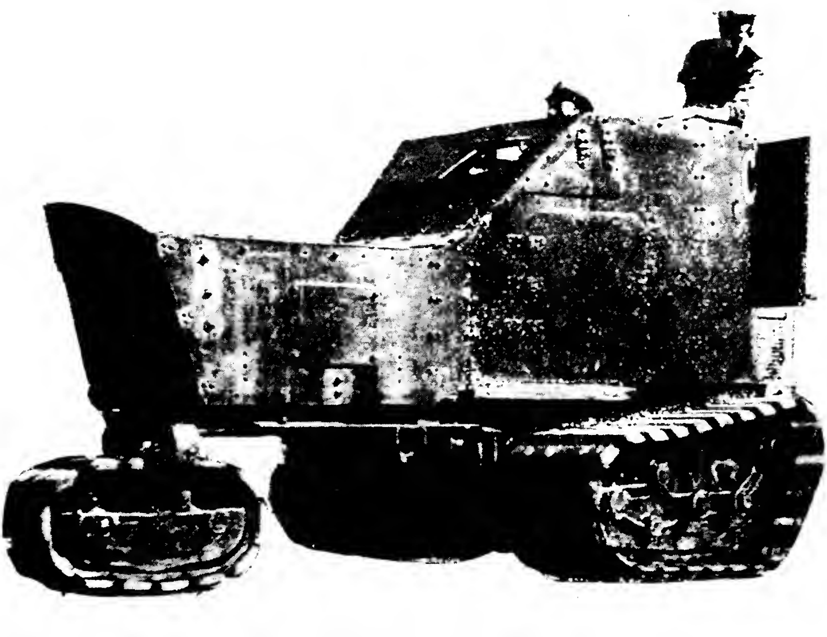


Fig. 1.1 First tracked armoured vehicle consisting of a Delaunay-Belleville armoured car body on a Killen-Strait tractor.

number of designs which included a vehicle with large, 4.6 m diameter wheels and an articulated tracked troop carrier (1.18). But all these designs were rejected by the end of July 1915 in favour of the concept of a single-unit tracked vehicle with a turret-mounted gun. By then the Landships Committee had also procured from the United States two tracked tractors from the Bullock Tractor Company and a light Killen-Strait tractor, which were used by the RNAS Armoured Car Division to carry out demonstrations and experiments in support of the Committee's activities (1.19). One of them involved the mounting of the body of a Delaunay-Belleville armoured car on the Killen-Strait tractor and this, in July 1915, created the very first, if only experimental, tracked armoured vehicle.

However, it was the tracks of the Bullock tractors which were adopted, in a modified form, for the vehicle the Landships Committee decided to design and build. The order for it was given to the tractor firm of William Foster and Co of Lincoln, who built it using the engine and the transmission of its wheeled tractors and who had it running in September 1915, albeit with a dummy turret. Its turret apart, the vehicle amounted to a simple box hull of boiler plate mounted on tracks. Its tracks did not prove entirely successful but it represented, nevertheless, the first attempt at a design of a tank which resulted in an actual vehicle.

The first experimental tank, or landship as it was called at the time, became known as Little Willie but although its tracks were rebuilt it was quickly abandoned in favour of another type which was designed by Lieutenant W G Wilson and which was also built by Foster and Co. The second landship was designed to meet a new requirement from the War Office, which was finally becoming involved in the development of landships, that they should be able to cross trenches 1.5 m wide and with parapets 1.4 m high (1.20). This requirement actually originated with Swinton, who based it on the information about contemporary German trenches, and it represented the only influence he actually exercised on the design of the landships.

To meet the new requirement Wilson devised a novel layout of the tracks which was much longer and higher than before and which made the tracks run round the body of the vehicles instead of being under it, as well as making them rise steeply at the front to a high idler wheel. All this made for good obstacle crossing but it required any gun turret to be located undesirably high. An alternative solution was therefore adopted, which was borrowed from the field of contemporary warship construction and which involved the mounting of guns in sponsons projecting out of the sides of hull. The guns were two naval 57mm 6 pounders, which were the only guns of sufficient size that were available. In addition the vehicle was armed with three machine guns.

The second landship was completed in January 1916, when it was first successfully demonstrated. A second and equally successful demonstration to government ministers and senior army officers followed in February 1916, after which the War Office asked for 100 similar vehicles to be built for use by the British Army in France.

One hundred and fifty were actually ordered and the first of them were delivered in June 1916. One half of the total were virtually replicas of Wilson's prototype landship, which became known as Mother. The others differed in being armed only with five machine guns, as a result of Swinton's curious notion that the gun-armed tanks should be supported by others with more machine guns, lest they be overwhelmed by an onrush of enemy infantrymen (1.21).

The two versions of the Mark I tank weighed 28 and 27 tons, respectively, and each was manned by a crew of eight. Like the two prototype landships, they were

powered by a 105 hp Daimler tractor engine, which gave them a maximum speed of 5.9 km/h, and they had an estimated range of 37 km. Most of the British tanks built later during the First World War were of a similar pattern, although they were improved in detail and their weight rose to 37 tons with the Anglo-American Mark VIII (1.22).

Almost simultaneously, and quite independently of the events in Britain, tanks were also developed in France. As in Britain, the development of tanks in France originated with armoured cars and in particular with studies to improve them on which Schneider and Company embarked in January 1915. This led Schneiders to purchase two Holt tractors and, after trials with them, to design in August 1915 what was called an "armed and armoured tractor". Work on it was then interrupted by a demand that it be developed into a carrier of a barbed wire cutting device, which represented a wasteful preoccupation of some officials with only a small part of the problem facing the armies in the field.

By then, however, Colonel J E Estienne had seen a Holt tractor being used by the British artillery and in December 1915 put forward the idea of an armed and armoured tracked 'land battleship' for breaking through enemy trench lines. This gained almost immediately the approval of the French Commander-in-Chief, General J Joffre and, as a result, Estienne discussed his ideas with M Brillie, the engineer who had been working at Schneiders on their tracked armoured vehicle projects. Brillie then produced the design of a tank which was accepted and in February 1916, only a few days after the first British tanks were ordered, the French Ministry of War placed an order with Schneider for 400 vehicles.

But the first Schneider tank was not built until September 1916 and the production of the rest was much slower than that of the British tanks. At 13.5 tons they

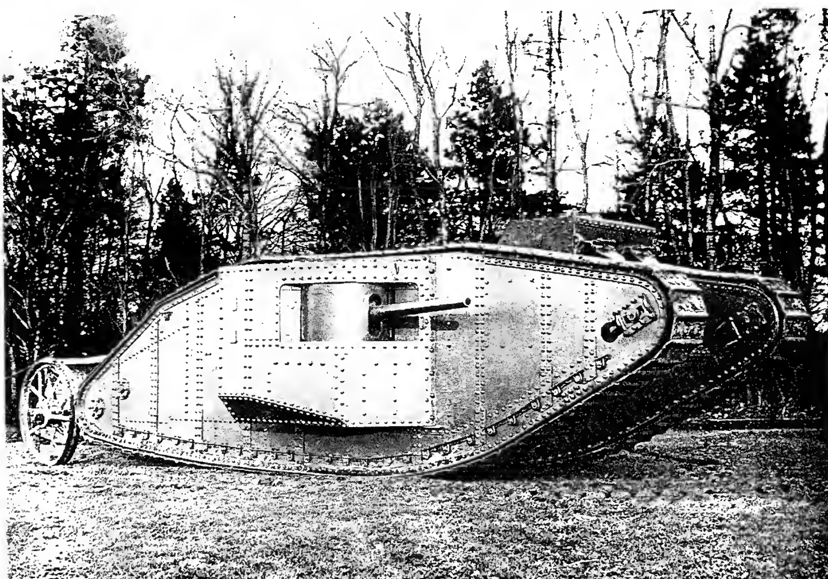


Fig. 1.2 Big Willie, or Mother, the prototype of the first British tanks. (Imperial War Museum)

were lighter than the latter but their main armament was more powerful, consisting of a 75mm gun. However, they had none of the British tanks' obstacle crossing capability. The same applied to the second and somewhat heavier French tank, the 23 ton St Chamond, which was also armed with a 75mm gun.

The third type of French tank, the Renault FT, was very different from all the earlier tanks in being much smaller and lighter. Its development, like that of the first French tank, was inspired by Estienne but it was executed under the direction of L Renault. It came to weigh 6.5 to 7 tons and was manned by a crew of only two men. Its maximum speed of 7 km/h was no higher than that of the two earlier French tanks but it was the first tank to be produced with a rotating turret, which mounted either a single machine gun or a short 37mm gun. The first was completed in April 1917 and within its capabilities it proved very successful, becoming subsequently a model for other tanks as well as being widely used itself (1.23).

1.3 Use of Tanks during and after the First World War

Although technology governed what could be done, its scope was sufficiently wide to provide a range of options in the design of tanks. In consequence, tanks came to vary considerably as these options were exercised to suit different ideas about their role or mode of employment.

The early ideas on the employment of British tanks were mainly those of Swinton who was made commander of the first British tank unit and who, in 1916, defined the tank as "primarily a machine gun destroyer, which can be employed as an auxiliary to an infantry assault" (1.24). In other words, he regarded tanks as specialised vehicles which would help the infantry assault enemy trenches.

British tanks were, in fact, originally used as such. They were first sent into action, on the Somme, on 15 September 1916, when only 49 could be made available. Their first employment ignored Swinton's advice that they should be

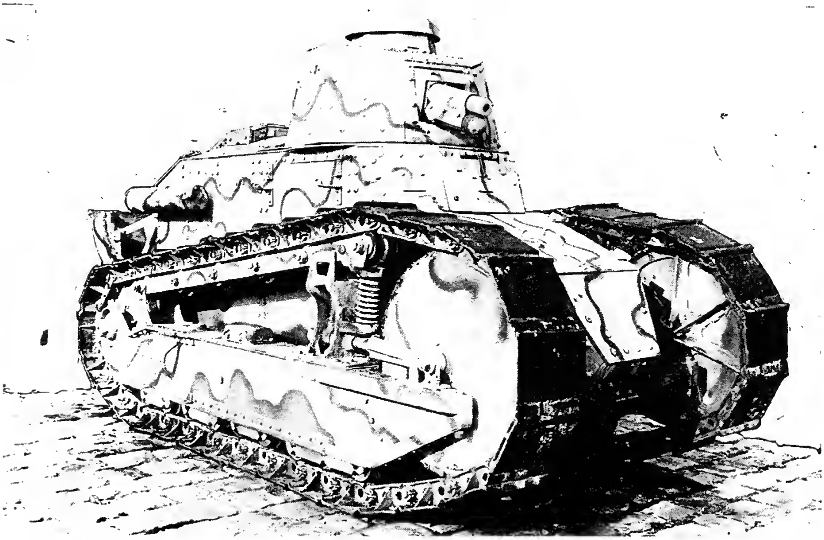


Fig. 1.3 French Renault FT light tank of 1918. (French Army)

used by surprise and not in driblets and it met with relatively little success. It was only a year later, on 20 November 1917, at Cambrai, where 476 tanks were concentrated on a narrow front and used in a surprise assault over suitable ground, that tanks achieved a spectacular success in the role for which they were intended.

However, the battle of Cambrai also demonstrated that the capabilities of the original tanks did not extend beyond the short-range assault for which they were designed. To advance beyond it there had to be another, faster type of tank with a longer operating range which could exploit any breakthrough achieved by the other tanks. A lighter and faster tank, which became known as the Medium A, had already been designed and the first production model of it was completed shortly before the battle of Cambrai. But it was not used on any scale until the second major tank assault, at Amiens in August 1918, for which a total of about 600 tanks of all types was assembled.

Thus, by the end of the First World War in November 1918 the British Army had two categories of tanks. One consisted of the direct developments of the original tank, which culminated in the Anglo-American Mark VIII heavy tank. The other consisted of the Medium A and its successors. The role of the latter was about to be extended considerably as a result of experiments carried out by the engineering staff of the Tank Corps which showed that a tank could be built to have a maximum speed of 30 km/h, or more than twice the speed of any tank built until then. This inspired Colonel J F C Fuller, who was the chief of staff of the Tank Corps, to produce "Plan 1919", which proposed the use of fast medium tanks for raids against objectives well behind enemy lines (1.25). The raids were to be carried out by tanks called Medium D, which still had to be designed but work on which was started in 1918 by Lt. Colonel P Johnson. However, by the time a prototype of it was built the war was over.

By then a total of 2636 tanks had been built in Britain but many of them had become casualties and plans to produce more were quickly abandoned. What is more, the further use of tanks was questioned, because they were still only considered to be instruments of trench warfare, which was not expected to occur again. This attitude was epitomised by a general who said in a 1919 lecture on the next war "The tank proper was a freak. The circumstances which called it into existence were exceptional and are not likely to recur" (1.26). Nevertheless, some tanks were retained but the strength of the British tank forces shrunk after the war to four battalions.

France was left with a much higher proportion of the 3977 tanks it had produced, although almost all of its tanks were the light Renault FT. In fact, with the addition of those completed after the war, the French Army had a stock of as many as 3737 tanks of this type in 1921 (1.27). This was more than the number of tanks that all other armies had at the time and, together with its prestige, made the French Army and its ideas dominate the tank scene for some time.

The French Army regarded the Renault FT as an infantry accompanying tank and in 1920 made all its tank units a part of the infantry. This was in keeping with the traditional ideas about the primacy of the infantry and matched the capabilities of the Renault FT. However, it meant that tanks were confined to the role of a slow-moving auxiliary and although the Renault FT proved effective in supporting the infantry as time went on this represented less and less what tanks could do.

Nevertheless, other countries followed the example of France. The first two were the United States and Italy, the only other countries to embark on the manufacture of tanks during the war apart from Germany, which only produced

about 20. Thus both the United States and Italy made tank units a part of the infantry and both copied the Renault FT. The US copy was the M1917 light tank, 952 of which were completed after the war (1.28); the Italian copy was the Fiat 3000, of which 100 were built (1.29).

However, even before the infantry took over the French tank units, or the *artillerie d'assaut* as they were called until then, Estienne, who had become their commander, was already forecasting a very different way of employing tanks. Thus, in a study written in 1919, he foresaw the light accompanying tanks of the Renault FT type becoming after a time the organic equipment of the machine gun or heavy weapons companies of the infantry. They would then be succeeded by battle tanks which would be capable not only of destroying enemy machine guns but also enemy tanks. Companies of these tanks would replace infantry companies as the basic fighting units and future battles would be fought between tanks, whose armour and armament would need to be increased progressively. Other lighter and faster tanks might be useful for exploiting the success of the more powerful tanks, but Estienne very wisely commented that it would be a mistake to allow their construction to reduce the effectiveness or the number of the battle tanks, as the latter could never be too powerful or too numerous (1.30).

But Estienne's far-sighted views were ignored and, after several years of trying to improve the Renault FT, the French Army procured some more, albeit it more modern, infantry accompanying light tanks. The prime example of them was the Renault R-35, which became the most numerous French tank by 1940.

In the meantime more new ideas on the employment of tanks emerged in Britain and they led to its progress well beyond the confines of infantry support. To start with, in 1919, Fuller proposed that infantry battalions be reorganised to include a company of tanks (1.31). This foreshadowed the integrated tank-infantry battalions which were successfully created forty years later by the French and Swedish Armies but it could hardly be implemented at the time for lack of suitable tanks. Thus, the wartime British tanks were too clumsy to be incorporated within infantry battalions. A Light Infantry Tank was proposed but it still had to be designed and it was even faster than the Medium D, although Fuller considered that this did not make it incompatible with infantry marching on foot (1.32).

Fuller's proposal did not lead to any practical results but his writings and those of others promoted the formation, in 1927, of an Experimental Mechanized Force to explore some of the new ideas about a more mobile employment of tanks. The pursuit of these ideas was greatly helped, and to some extent inspired, by the Vickers Medium tanks with which the Royal Tank Corps was reequipped from 1923 onwards and which had a maximum speed of about 30 km/h – a speed considerably higher than that of all tanks used previously. In fact, a battalion of these tanks formed the core of the Experimental Mechanized Force. The latter also contained motorised infantry, artillery, reconnaissance and engineer units and thus constituted the first attempt at a self-contained force based on automotive vehicles. As such it provided some valuable experience but experiments with it led to two divergent lines of employment, neither of which made the most effective use of tanks.

One line of development led towards mobile formations composed almost entirely of tanks. The idea of tanks operating by themselves was inspired by the example of warships and already found expression in 1916 in a study written by Captain G le Q Martel (1.33). It described a future army composed almost entirely of tanks, different types of which would correspond to the principal types of contemporary warships. The naval concept of tank warfare was subsequently

taken up by Fuller, who in 1932 described the offensive wing of a future mechanised army as consisting, in effect, only of tanks, "which will operate on somewhat similar lines to a fleet at sea" (1.34).

Views like this ignored the fundamental difference between the sea and ground environments and grossly overestimated the effectiveness of tanks operating by themselves. But the employment of tanks in 'all-tank' formations made it much easier to exploit their mobility than in cooperation with other arms. This recommended it to the tank enthusiasts, particularly when they were only faced with the problems of peacetime manoeuvres. Thus from 1931 onwards further experiments carried out in Britain were based on a brigade consisting only of four tank battalions.

The tank brigade proved a considerable advance in mobility on the contemporary infantry and cavalry formations. But, being composed only of tank units, its capabilities were limited and its effectiveness was confined to the exploitation of success won in battle by other formations, which was the role that horse cavalry had previously performed. In spite of this, the tank brigade was accepted in the 1930s as a basic mobile armoured formation and although the concept of 'all tank' formations was subsequently discredited, a tendency to return to it manifested itself again in the British Army in the 1950s and in the German Army during the 1980s.

A lesser legacy of the application of naval concepts to tanks has been the practice of equating them with battleships. Since the virtual demise of battleships after the Second World War this has often led to claims that a similar fate was about to overtake tanks. But this has not happened for the very simple reason that the comparisons between them are not generally valid. Thus, some tanks could be compared, perhaps, with battleships and particular types of them certainly become obsolete periodically. However, in general, tanks are not the equivalent of a particular type of warship but of warships as a whole and just as the latter remain viable in different forms, despite the demise of the battleships, so do tanks.

The second major outcome of the experiments started in Britain in 1927 was the creation, or re-creation, in 1934 of tank units for close cooperation with the infantry. These units were subsequently organised by the British Army into Army Tank Brigades, which were allotted to infantry formations in much the same way as the tank units of the First World War.

Thus the quest for new methods of employing tanks resulted in the creation of two categories of tank units in keeping with the traditional division of armies into 'horse' and 'foot'. This was foreshadowed in the first British Army armoured force manual which was issued in 1929 under the title *Mechanised and Armoured Formations* and which divided the army, including its tank units, into 'combat troops' and 'mobile troops'. But there was no fundamental reason for such a division, which was due to a wrong inference being drawn from the limited mobile role to which horse cavalry was reduced towards the end of its existence. Thus it was inferred that cavalry, and other mobile troops, were only capable of such a role and, therefore, that other troops were needed to do the fighting. In fact, at its best, cavalry could cope with all the fighting by itself, as it did from the Parthian cavalry of Surenas in the first century BC and the Mongol horsemen of Ghengis Khan to the Confederate cavalry of General N B Forrest and the cavalry corps of General J H Wilson on the Union side of the American Civil War (1.35). Nevertheless, the view that armies had to be divided into the two categories of troops was generally accepted and as late as 1944 the British Army divided its tanks between tank brigades "designed for close co-operation with the infantry, especially in breaching

enemy defences" and armoured divisions "designed for exploitation after the enemy's position has been broken into" (1.36).

A similar division was adopted during the 1930s in France. There the gradual mechanisation of the cavalry produced the *Divisions Légères Mécaniques* which were, in effect, armoured divisions but which were intended to perform much the same limited role as horse cavalry divisions. The majority of the infantry's tanks were still the light accompanying tanks but its more powerful *chars de manoeuvre d'ensemble* were concentrated into *Divisions Cuirassées*, whose principal role was to be that of assault on enemy positions (1.37).

Russian tanks were also generally divided between battalions of light tanks intended for close infantry support, like the French *chars d'accompagment*, brigades of more powerful tanks which corresponded, roughly, to the *chars de manoeuvre d'ensemble* and mechanised brigades composed mainly of fast tanks, which were to be used in a cavalry role either by themselves or combined with other arms in mechanised corps.

The mould of tradition, which confined tanks to infantry support or to the limited role of horse cavalry, was not broken until the creation in Germany in the mid-1930s of the Panzer divisions. These were based on tanks but in close combination with other arms, brought up as far as possible to the tanks' level of mobility. What is more, they were regarded as versatile fighting formations which were both more mobile and had greater striking power than other contemporary formations. As a 1940 German manual put it, a Panzer division "combines great fire power with high mobility" and is suited to "rapid concentration of considerable fighting power, obtaining quick decisions by breakthroughs, deep penetration on wide fronts, and the destruction of the enemy" (1.38).

The idea of versatile mechanised or armoured forces made up of tanks, mechanised infantry and self-propelled artillery had already been put forward in the early 1920s by General Estienne in France (1.39), and by Captain B H Liddell Hart in Britain (1.40). Others wrote about it later, including Colonel C de Gaulle in France (1.41), and General L von Eimannsberger in Austria (1.42). But it was the creators of the *Panzerwaffe*, and in particular General H Guderian, who first put it into effect.

Once they demonstrated their effectiveness in the early stages of the Second World War, in Poland in 1939 and in France in 1940, the Panzer divisions became a model of the most effective use of tanks. In particular, they set a new pattern in the employment of tanks as a highly manoeuvrable source of fire power which has been followed to a large extent ever since.

1.4 Evolution of Tanks from 1918 to 1939

When the First World War ended there were, broadly speaking, two categories of tanks. One consisted of tanks of 20 to 40 tons which were armed with guns of 57 to 75mm and which were intended for assaulting or breaking through enemy positions. The other category consisted of lighter tanks, which ranged in weight from 6.5 to almost 20 tons but which were armed only with machine guns or, at most, with 37mm guns. The great majority of them and in particular the Renault FT and its derivatives were intended for close infantry support.

Before the war ended much heavier tanks began to be developed in France and in Germany. In France this led to the 2C tanks of 68 tons, each of which was manned by a crew of 12 and was armed with a 75mm gun mounted, for the first time, in a turret. However, only ten of these tanks were completed, after the war

(1.43). In Germany construction began of two *K-Wagen*, which weighed about 150 tons and which were armed with four 77mm guns, mounted in sponsons. Each was to be manned by 22 men but both were destroyed after the war when they were about to be completed (1.44). The 2C tanks remained in service with the French Army until 1940, when they were destroyed without ever going into action but for two decades they were the heaviest tanks in use anywhere.

Nothing more was done about the development of tanks as heavy as this after the First World War when armies were generally concerned with much lighter vehicles. In particular, the French Army planned to develop a replacement for the Renault FT. But a successor to it, the Renault R-35 light tank, was not put into production until 1935. With a maximum speed of 20 km/h it was significantly faster and the maximum thickness of its armour was 40mm instead of 20mm. But the general concept of the two-man R-35 was much the same as that of its predecessor and its main armament consisted of the same short-barrelled 37mm gun as that mounted in the Renault FT. This showed a remarkable lack of concern about the most important characteristic of tanks, which is their armament, and made the R-35 virtually incapable of fighting other tanks.

Much more sensibly, the French Army also embarked on the development of a *char de bataille* armed with a 75mm gun, albeit mounted in the hull (1.45). But this was not put into production until 1934 in the form of the 27 ton Char B.1, which was quickly made obsolescent by the appearance of other, more recently developed tanks.

Better progress was made in Britain. It started with the recognition by the engineering staff of the Tank Corps that the speed of tanks could be increased by the use of sprung suspensions, which none of the British war-time tanks had, and by the use of higher powered engines. This led to the design of the 20 ton Medium D, which had a higher power-to-weight ratio than any previous tank and a maximum speed of about 30 km/h, or more than twice the speed of any British or French tank built until then. But even this was improved upon by the 8 ton Light Infantry Tank derived from the Medium D which, on trials in 1922, attained a speed of 48 km/h (1.46). The two tanks represented therefore a considerable advance in mobility and they were also amphibious, at least to the extent of being able to swim across calm inland waters. But their design also incorporated a number of dubious features. These included a suspension consisting of a cable interconnecting all the road rollers on each side and a single spring, pivoted track plates in the case of the Medium D and laterally flexible tracks with spherical joints between the track plates in the case of the Light Infantry Tank. Moreover, both had fixed turrets and although some of the Medium D were to have a 57mm gun the rest were to be armed only with machine guns. What is more, the maximum thickness of their armour was only half that of the Renault FT. As fighting vehicles they therefore left much to be desired but it was mechanical troubles and financial stringency which led to a decision in 1922 to abandon them.

At the same time the British Army decided to order the second of two tanks designed by Vickers Ltd. as competitors to the Light Infantry Tank (1.47). This tank, which became known as the Vickers Medium, was not quite as fast as its competitor but it was capable of about 30 km/h, which put it well ahead of most contemporary tanks and enabled the Royal Tank Corps to take a lead in the development of more mobile methods of employing tanks. Its high speed was made possible by a properly sprung suspension and it was sensibly armed with a 47mm gun. What is more, in contrast to the one-man turrets of the tanks being

developed in France, its turret accommodated a gunner and a commander who, being free of the task of firing the gun, could better exercise his craft. On the other hand, it suffered from the contemporary preoccupation with machine guns, having as many as six of them which could hardly be operated by its five-man crew. Also its armour was at first only 6mm thick. Nevertheless, in spite of its various shortcomings and the criticism levelled at it at different times, the Vickers Medium represented an important step forward in the development of tanks. It was also the only tank produced in quantity during the 1920s anywhere in the world, even though the total was not more than about 160 vehicles.

After the Vickers Medium entered service attention in Britain turned to much lighter vehicles. These were conceived, like the Renault FT, as small, light tanks for use with or by the infantry. But after a number of vehicles was tried between 1925 and 1927 it was decided that there was a need for two different light armoured vehicles: one was a machine gun carrier for the infantry and the other a reconnaissance tank, with a turret, for the armoured units (1.48).

The machine gun carrier became the Carden-Loyd Mark VI. It was a small, open-top vehicle of 1.5 tons which had a crew of two and 305 of which were produced by Vickers-Armstrongs Ltd. for the British Army and for export. It advanced tank design by having a new, short-pitch track which was potentially more durable as well as being quieter than the earlier types of tracks. But it was too small to be an effective carrier of the infantry's heavy machine guns and its value as a fighting vehicle was highly questionable. Nevertheless, it aroused a great deal of interest when it appeared, although on account of its low cost as much as of its military characteristics, and it was copied as a turretless tankette in the Soviet Union, Poland, Czechoslovakia and Italy. Its Italian derivative, the 3.2 ton Carro Veloce L.3, even became the principal armoured vehicle of the Italian Army, which had about 1200 vehicles of its type by the outbreak of the Second World War (1.49). But it proved of little value when it came to fighting.

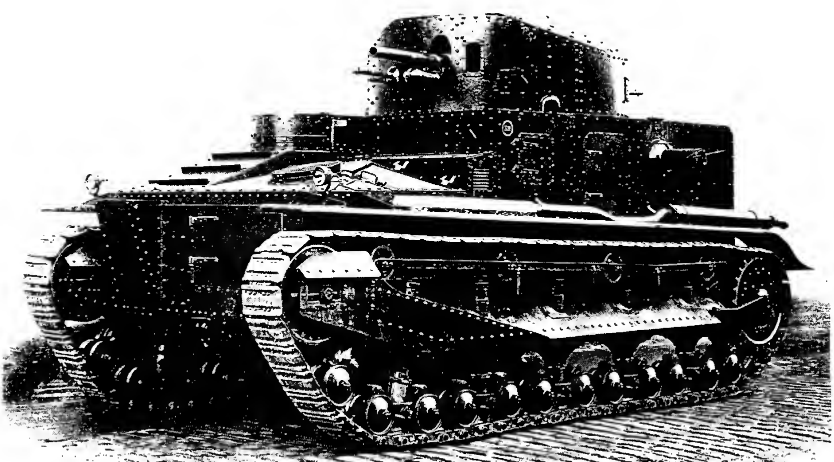


Fig. 1.4 Vickers Medium Mark I. (Vickers-Armstrongs)

The light tanks which originated at the same time as the Carden-Loyd Mark VI were a somewhat better proposition, particularly for reconnaissance and for fighting lightly armed enemy forces. But they were only small, two-man vehicles armed with machine guns. As fighting vehicles they represented, therefore, no advance on the Renault FT, except for being more mobile. In fact, they were capable of speeds of more than 50 km/h. They were also simple to operate, relatively reliable and, above all, less expensive than more effectively armed tanks. This led to them being acquired in considerable numbers by the major armies which did not, however, require them at the time for anything more serious than peacetime manoeuvres and training or, in a few cases, internal security operations. Their use also spread, in small batches, to smaller armies which through them were able to acquire token forces of tanks.

The first of these light tanks was the Carden-Loyd Mark VII, which was built in 1929 and which was followed by a series of Vickers Carden Loyd light tanks produced for the British Army (1.50). Similar light tanks, some of them amphibious, were also built by Vickers-Armstrongs for a number of other armies and their lead was followed by the design and production of tanks of their type in a number of countries. These included the Russian T-33, T-37 and T-38, French AMR Renault Model 1935, German Pz.Kpfw.I and Japanese Type 94 tankette.

From the Mark V of 1935 onwards, British light tanks were improved by being built with two-man turrets and armed with a 12.7mm heavy machine gun in addition to the customary, rifle-calibre machine gun. This gave them some anti-tank capability, although only against tanks as lightly armoured as themselves. In spite of this and their other limitations, 1002 of the 1148 tanks produced in Britain up to the outbreak of the Second World War were lights tanks (1.51).

Financial considerations, which made the relatively cheap light tanks so attractive to armies, did not inhibit them from going to the other extreme and trying to develop tanks that were large and expensive. In particular, the British Army planned to replace its Vickers Medium with a tank officially designated the A.6 and commonly known as the Sixteen-tonner (1.52). This tank, which was designed by Vickers-Armstrongs in 1927, was a considerable advance on the Vickers Medium in having a better layout with a separated engine compartment at the rear of the hull and a three-man turret, and it was capable of up to 48 km/h. But at 14mm the maximum thickness of its armour was not greater than that of the contemporary light tanks and less than that of the Renault FT. What is more, its main armament consisted of a 47mm gun, which was virtually the same as the gun already used for several years in the Vickers Medium. The use of this gun was hardly compensated for by the addition of two small turrets, each with two machine guns, which were incorporated in the Sixteen-tonner at the express request of the Royal Tank Corps.

The penchant for additional machine gun turrets was not confined to the British Army. The French 2C heavy tank already had a second machine gun turret at the rear of the hull and so did the 16 ton *Grosstraktoren* built secretly in Germany in 1929 (1.53). The very first Japanese tank built in 1927 went further in having an additional machine gun turret at the front as well as the rear (1.54). The 19.5 ton *Neubaufahrzeuge* built in Germany in 1934 also had two machine gun turrets (1.55). But the provision of additional machine gun turrets was carried to an extreme in the A.1 Independent heavy tank built in Britain in 1926 which had no fewer than four (1.56).

This aberration in tank design can be ascribed in part to the influence of naval ideas and the concept of the employment of tanks by themselves, which required

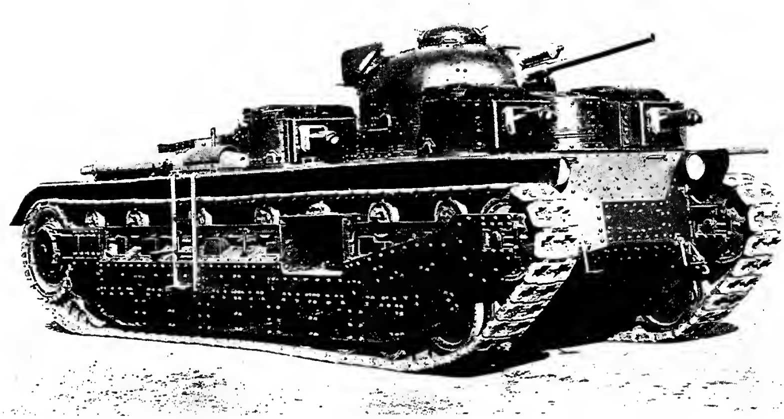


Fig. 1.5 British Independent tank with five turrets. (Vickers-Armstrongs)

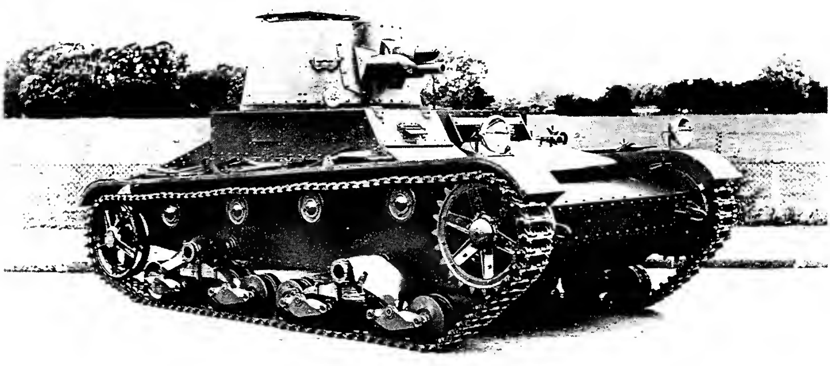


Fig. 1.6 Vickers-Armstrongs Six-Ton Tank. (Vickers-Armstrongs)

them to ward off attacks from all quarters. In part it was also due to the contemporary tendency in Britain to overrate the effectiveness of machine guns and to ignore the need to arm tanks with guns of more than small calibre (1.57). This tendency was clearly demonstrated by the main armament of the 32 ton Independent which consisted only of a 47mm gun.

The other multi-turreted tanks, such as the *Grosstraktoren* and the *Neubaufahrzeuge*, did at least mount 75mm guns in their main turrets. Multi-turreted tanks built in the Soviet Union were similarly armed with 76.2mm guns. They included the 17 ton T-28 first built in 1932, which had a machine gun turret on either side of the driver, like the British Sixteen-tonner, and the 45 ton T-32 and T-35, built in 1930 and 1933 respectively, which had five turrets like the Independent.

The 75 or 76.2mm guns mounted in German and Russian multi-turreted tanks were what the tanks of the period should have been armed with in general. Although they were short-barrelled, they fired projectiles which were effective against the armour of the contemporary tanks. At the same time they were of sufficiently large calibre to fire high explosive shells that were effective against various other targets. In consequence, tanks armed with them became what they basically are, namely a mobile source of fire power effective against virtually all battlefield targets. As versatile tank weapons they differed fundamentally from the 93.4mm mortars mounted in the close support versions of the Vickers Medium and other British tanks which were specialised weapons, intended primarily to fire smoke shells and never provided with armour-piercing ammunition.

However, the need to arm tanks with 75 or 76.2mm guns was only generally accepted during the Second World War. Until then they were mounted only in a relatively small number of the more powerful tanks. The most notable of them was the German Pz.Kpfw.IV, which was developed to be the most powerful tank of the Panzer divisions (1.58). This 75mm gun tank, which weighed 17.3 tons when it was first built in 1937, dispensed with the unnecessary complication of the additional machine gun turrets but provided room alongside the driver for a radio operator who also fired a hull mounted machine gun. Pz.Kpfw.IV also had a relatively roomy, three-man turret which allowed for an effective division of tasks between the commander, gunner and loader. The maximum thickness of its armour was initially only 15mm and the leaf springing of its road wheels was not up to the standard of the better of the contemporary tank suspensions. Nevertheless, it was in general the most effective tank of the late 1930s.

In the meantime another category of tanks had come to the fore. It consisted of light tanks larger and heavier than those of the Vickers Carden Loyd pattern and armed not only with machine guns but also with 37 to 47mm guns. Unlike the lighter tanks they were capable, therefore, of fighting other contemporary tanks and they were also generally more effective tactically because they had two-man turrets.

The experimental German *Leichttraktoren* built by Krupp and Rheinmetall in 1930 were an early example of this category of light tanks (1.59). However, tanks of this kind did not begin to come into prominence until the appearance of the Six-ton Tank designed by Vickers-Armstrongs as a private venture. In its original version built in 1928, the Six-ton Tank had two machine gun turrets, but by 1930 it was developed into a much more sensible vehicle with a single two-man turret mounting a 47mm gun and a machine gun. In this form the Six-ton Tank had a main armament of the same calibre as the A.6 medium tank which was then being developed for the British Army. The maximum thickness of its armour was also similar but it was much less expensive. Nevertheless, the British Army would not consider it, although it represented potentially far better value for money than either the A.6 type of medium tank or the poorly armed Vickers Carden Loyd light tanks.

The Vickers-Armstrongs Six-ton Tank was however, purchased by a number of countries. It was also copied in the Soviet Union, where it was produced on a large scale from 1931 onwards as the T-26, and in Poland, where it was produced as the 7TP. Tanks with similar general characteristics were also produced in other countries. They included the Landsverk 10, or Strv m/31, built in Sweden in 1930, and the TNH and LT-35 built in 1935 in Czechoslovakia.

Although they were lighter than the contemporary medium tanks but because they were armed with guns of the same calibre as some of the latter, tanks of this

kind could be regarded as 'light-medium' rather than light tanks. This would certainly be true of the most successful of them, the BT which was built in large numbers in the Soviet Union. The BT owed its origin to the outcome of several years' work in the United States by J W Christie on fast tanks which could run on wheels as well as tracks, an idea explored in several different forms during the 1920s. The most notable outcome of this work was an experimental vehicle built by Christie in 1928 which attained what was then a record speed of 68 km/h (1.60). A small number of T3 and T4 tanks was built from its basis between 1931 and 1936 for the U.S. Army, which did not however develop them any further (1.61). But in 1930 Christie sold two chassis to the Soviet Union, where they served as the basis for the design of the BT, which began to be produced by the end of 1931.

Of the major features which the BT inherited from Christie, the ability to run on the road wheels after the removal of the tracks proved of little value. But the BT very successfully followed Christie's ideas in having large, independently sprung road wheels and a high power-to-weight ratio. In 1933 the Russians added to this a 45mm gun and the BT became what was probably the most effective tank of the mid-1930s.

Six years after the Russians adopted Christie's ideas the British Army took note of what they had achieved with the BT and decided to use his type of suspension for British tanks (1.62). In the meantime, the A.6 Sixteen Tonner and the Mark III Medium derived from it had been abandoned as too expensive and an attempt to produce a cheap medium tank with three turrets, the A.9, did not prove a success. The next tank to be designed, in 1934, the A.10 was much more sensible as it dispensed with the additional machine gun turrets. What is more, its original, A.10 E.1 version introduced what was to become many years later the standard configuration of tanks, with only the driver at the front, a three-man turret in the centre and the engine and transmission compartment at the rear of the hull. This configuration was then combined with a Christie-type suspension to produce in 1938 a new tank, the A.13.

The A.13 was somewhat larger than the BT but it was superior to it in having a three-man turret and short-pitch tracks, instead of Christie's noisy long-pitch tracks with which the Russians persevered. It also dispensed with Christie's idea that tanks should be able to run on their road wheels without tracks as well as with them, which was rightly adjudged in Britain to be an unjustified complication. Otherwise the general characteristics of the two tanks were similar, which included their weight of 13.8 to 14 tons. Thus A.13 had the makings of a highly mobile, light-medium tank that could be used effectively in a number of roles. Unfortunately it was not regarded as such but as a more specialised 'cruiser' tank intended to be used in the cavalry role to which British armoured formations were being confined (1.63).

What is more, those in charge of British tank development still hankered after multi-turreted tanks and in 1938 placed orders for the A.14 and A.16 'heavy cruisers'. Each of these, once again, had two additional machine gun turrets but neither mounted in its main turret a gun larger than that of the A.13. Development of the A.14 and A.16 was mercifully abandoned in 1939 but the tank which followed the A.13 cruisers, the A.15 or Cruiser Tank Mark VI, Crusader, still had one additional machine gun turret and the same 40mm gun as the A.13.

To make matters worse, no other tank was developed in Britain with a more powerful gun. Instead, in 1934, the British Army decided to develop a second specialised category of tanks for infantry support, none of which was more heavily

armed than the contemporary cruiser tanks. In fact, the Infantry Tank Mark I, first built in 1936, was armed only with a single machine gun and except for its thicker armour represented in essence no advance on the Renault FT concept, which was then 20 years old. Infantry Tank Mark II, Matilda, was much better, having the same sensible layout as the A.10 E.1 and the A.13 and armour up to 78mm thick. But, in spite of its weight of 26.5 tons, its main armament was still only a 40mm gun. Moreover, its gun was not only of a relatively small calibre, but only fired solid shot which made it ineffective against such important targets as enemy anti-tank guns.

1.5 Development of Tanks during the Second World War

As a result of the differences in attitude, policy and design which existed prior to it, when the Second World War broke out in September 1939 the tanks of the various armies differed considerably in their characteristics and in their intended method of employment. In consequence, when they were put to test their performance varied a great deal.

At the time French tanks numbered 2677 and by the time the German offensive against France began in May 1940 their number had risen to more than 3500, excluding some 1500 Renault FT which were still being used in various ways and a small number of modern tanks in French overseas territories. However, of this impressive total 2665 were the Renault R-35 and similar light tanks which were designed only for close infantry support and most of which were dispersed by battalions over a wide front (1.64, 1.65). In consequence, they proved ineffective against the German armoured forces which were concentrated over a narrow front and moved rapidly. The outcome of this was to discredit the concept of infantry support on which the R-35 and similar tanks were based.

The other French tanks, the medium S-35 and the heavy B-1, were well armoured and, by contemporary standards, well armed with 47mm guns as well as short 75mm guns in the case of the B-1. Moreover, they were concentrated respectively, in the *Divisions Légères Mécaniques* and the *Divisions Cuirassées*. But these divisions were also unprepared for the kind of mobile operations which the German armoured formations conducted and they were not deployed very effectively.

On 1 September, 1939, the total number of German tanks amounted to 3195, but of this 1445 were the light, machine gun armed Pz.Kpfw.I and only 211 were Pz.Kpfw.IV. However, in their opening campaign against Poland they did not meet any serious tank opposition. On the eve of the 1940 offensive against France there were still only 280 Pz.Kpfw.IV out of a total of 3379, although this now included 710 tanks armed with 37mm guns, among which were ex-Czech Pz.Kpfw.35t and 38t as well as Pz.Kpfw.III (1.66). Most German tanks were not therefore very powerfully armed. The striking successes achieved in 1940 in France by the German armoured forces were consequently due to the way the tanks were employed rather than to their characteristics. Thus, all 2574 tanks that were actually deployed were concentrated in the ten Panzer divisions which the German Army had at the time and nine of these were concentrated on a narrow front (1.67).

The Panzer divisions were even more successful in relation to the opposing forces in 1941 when seventeen of them, with a total of about 3350 tanks, spearheaded the German invasion of the Soviet Union (1.68). The total number of Soviet tanks at the time has been generally estimated at about 24000, which was

not only four times as many as the total number of German tanks but more than the number of tanks in the whole of the world outside the Soviet Union. Seventy five per cent of this total consisted of T-26 and BT tanks, both of which the Soviet Army regarded as light tanks. However, they were far better armed than other contemporary light tanks, including those which represented 37 per cent of the German tanks, and the BT was generally comparable to other 'light-medium' tanks. The large number of Soviet tanks was somewhat less formidable than it might appear because many of them were in a poor state, which has been reflected in claims that 73 per cent of the older types were in need of overhaul (1.69). Moreover, Soviet tank forces were in considerable disarray as a result of two reversals of policy. The first was a 1939 decision to abolish the tank corps, which until then contained a significant number of Soviet tanks, and to use tanks by brigades for infantry support. The second was a decision taken in July 1940, following the striking success of the German Panzer divisions in France, to reform mechanised corps on a large scale (1.70). But this decision was only partly implemented by the time the German forces attacked in June 1941. In addition, the Soviet tank forces were badly employed and as a result of it all they were almost anihilated, losing, according to German records, 17500 tanks (1.71).

In contrast to their ineffective employment, the development of Soviet tanks proved very successful. Its greatest achievement was the T-34 medium tank, which was developed from the basis of the BT. In particular, T-34 followed the example set as early as 1933 by some of the BT-5 and was armed with a 76.2mm gun. It also followed the final version of the BT series, the BT-7M or BT-8, in being powered by a newly developed V-2 tank diesel. In addition, the T-34 benefited from the experience gained during the Spanish Civil War with the BT-5, which showed that its maximum thickness of armour of 15mm on the turret and 22mm on the hull front was inadequate. Moreover, the T-34 finally dispensed with the unnecessary complication of being able to run on the road wheels without tracks as well as with them, which the BT tanks inherited from Christie. But, very sensibly, the T-34 retained the Christie-type independent suspension.

Fig. 1.7 Soviet Christie-type BT-7 tank.

All the features incorporated in the T-34 were originally embodied in the T-32 experimental tank built in 1939, prototypes of the T-34 itself being built in 1940. Production followed quickly and in May 1941, on the eve of the German invasion, there were already 967 T-34s (1.72). Compared with 517 Pz.Kpfw.IV the T-34 was not only more numerous but was superior in terms of fire power and mobility. It also had superior protection, even though the thickness of the Pz.Kpfw.IV armour had increased to a maximum of 50 to 60mm, raising its weight to 21 tons against 26.3 tons of the T-34.

After most of the older tanks were lost in 1941, the T-34s became the basic Soviet tanks in 1941 and 1942, when they were usually assigned by battalions or brigades to infantry divisions. Subsequently they were used increasingly within the framework of tank and mechanised corps, which were recreated in 1942. To meet the demand for it, the T-34 was produced on a very large scale. In fact, throughout the whole of the war its annual rate of production exceeded that of all the German tanks taken together, attaining a peak of 15812 in 1943, and by the end of June 1945 its production reached a total of 53497 tanks (1.73).

In addition to the T-34, the Soviet Union also produced the KV heavy tank and also some light tanks, although these no longer counted. The KV was designed in 1938 and was wisely selected in preference to two heavy tanks with two turrets, the T-100 and the SMK, which showed that the concept of multi-turreted tanks was still alive at the time in the Soviet Union as it was in Britain. Production of the KV started in 1940 with the result that 508 were available in May 1941 and by the time it came to an end in 1943 it amounted to more than 4700 tanks (1.74).

The KV was obviously produced in much smaller numbers than the T-34 and it proved to be far less important. It had armour up to 75, instead of 45mm thick and a three-, instead of a two-man turret but this resulted in its weight being 42.5 tons while its main armament was exactly the same as that of the T-34. Its thicker armour was intended to make the KV capable of attacking enemy positions in the face of contemporary anti-tank weapons and, in fact, initially provided it with a high degree of immunity. But its immunity was bound to be short lived and, as more effective anti-tank weapons appeared, the KV lost whatever advantage it had over the T-34. The continued use of the KV was briefly justified in 1943 when it was rearmed with an 85mm gun. But shortly afterwards the same gun was also mounted in the T-34 and, as there was little sense in producing two different tanks with the same main armament, the KV-85 was abandoned. In its place came the 46 ton IS-2, or Stalin, heavy tank. This tank was similar to the KV but had thicker armour of up to 120mm on the hull front, partly because it dispensed with the hull machine gunner of the KV. However, the most important difference between it and the KV was its much more powerful, 122mm gun.

Although the IS-2 was relatively heavy, it was not used like most earlier heavy tanks as a specialised assault or breakthrough tank. Instead, it was used primarily to support the medium T-34 tanks with its long-range gun and in particular to destroy enemy heavy tanks. In fact, it was developed to a large extent to counter the German Tiger heavy tank which had appeared by the end of 1942.

The Tiger was, in turn, one of the German responses to the appearance of new Soviet tanks in 1941 and in particular of the T-34. At the time the German Army had no heavy tanks, except for a few experimental vehicles. However, once the new Russian tanks were encountered the German High Command realised the need for tanks more powerful than the existing Pz.Kpfw.IV. In consequence two new tanks were hurriedly developed. One was the 56 ton Tiger, whose design incorporated some features of one of the earlier experimental tanks but which was

armed with a tank version of the 88mm anti-aircraft gun that had already proved highly effective as an anti-tank weapon. The other was a new medium tank which became the Panther, a 43 ton vehicle armed with a 70 calibre long, high velocity 75mm gun. The Panther began to be produced in January 1943 and, together with the Tiger, gave the German tank units a qualitative superiority over the Russian tank units. But both tanks were produced on a relatively small scale, the total production of the original Tiger I amounting to 1354 and that of the Panthers to 5976 (1.75). In consequence, there were not enough Panthers to reequip the Panzer divisions completely with them and the Tigers were generally held back in independent battalions.

Both tanks had the same general layout as Pz.Kpfw.IV and five-man crews but apart from having much more powerful armament and thicker armour they were much more advanced mechanically. As a result of its combination of characteristics the Panther came to be regarded as the best medium tank of the 1943-45 period while the second version of the Tiger became the most powerful tank to be used during the Second World War. Thus, Tiger II was armed with a higher performance 88mm gun which was 71 calibres long and which could pierce considerably thicker armour than the 122mm gun of the IS-2. It was also heavily armoured, its frontal hull armour being 150mm thick, although this contributed to its weight of 68 tons, which made it the heaviest tank used during the war. But the total production of Tiger II amounted to only 489 vehicles.

In the meantime, while the Tiger and the Panther were being developed, the existing German tanks were belatedly armed with more powerful guns. In particular, Pz.Kpfw.IV was armed in 1942 with more powerful 75mm guns, first 43 and then 48 calibres long, instead of the short barrelled gun of 24 calibres, which had been used in German tanks since the *Grosstraktoren* of 1929. In contrast, the

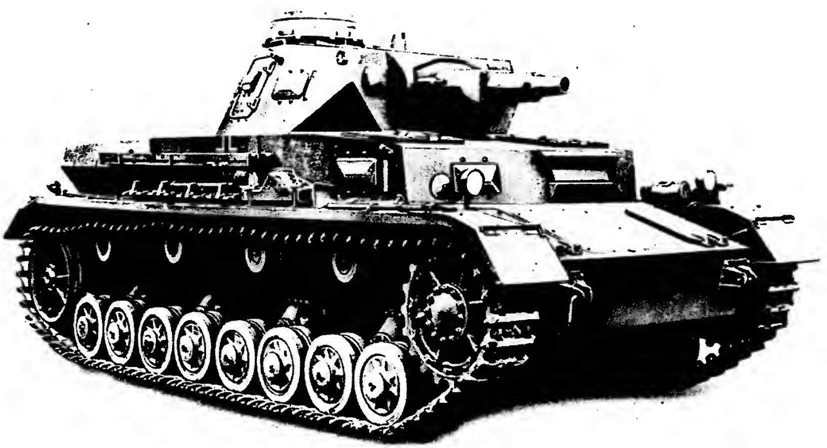


Fig. 1.8 German Pz.Kpfw.IV of 1939-1941.

Soviet Army armed its tanks with progressively longer barrelled and, therefore, higher velocity 76.2mm guns. Thus the early Russian tanks, including some of the BT, were armed with guns only 16.5 calibres long but the final versions of the BT and T-28 medium tank were armed with guns 26 calibres long while the original versions of the T-34 and KV had guns of 41.2 calibres. However, when the Pz.Kpfw.IV was finally rearmed with the 75mm L/48 gun the latter proved to have an armour piercing capability considerably greater than that of the Russian 76.2mm guns of 41.2 calibres and as good as that of the 85mm gun with which the T-34 was eventually armed.

The armament of the most numerous German tank during 1941 and 1942, the Pz.Kpfw.III, was also improved. The Pz.Kpfw.III was conceived as a light tank to be used alongside the medium Pz.Kpfw.IV (1.76). However, it had the same general layout, five-man crew and almost the same weight as the Pz-Kpfw.IV, which was extravagant in relation to its original armament of a 37mm gun. After the 1940 campaign in France it was rearmed with a 50mm gun 42 calibres long, which at short range could penetrate more armour than the short barrelled 75mm gun of the contemporary Pz.Kpfw.IV. However, its performance proved inadequate against the frontal armour of the Russian T-34. In consequence it was rearmed again, being fitted in 1942 with a 50mm gun 60 calibres long, the armour piercing performance of which was at least comparable to that of the Soviet 76.2mm tank guns of 41.2 calibres. In the end it was armed with the same 24 calibre 75mm gun as the original Pz.Kpfw.IV. This should have been done from the start and might have led to the merger of the two types into a single battle tank that could have been produced more efficiently and employed more effectively.

As it was, Pz.Kpfw.III was best used when its chassis became the basis of the turretless *Sturmgeschütz*. The latter was conceived as an assault gun for infantry support but in 1942 it was rearmed with the same long-barrelled 75mm gun as the Pz.Kpfw.IV. This turned it not only into a tank destroyer but also into a very effective turretless tank and it was used as such by the Panzer divisions when there was a shortage of turreted tanks. Ultimately the number of *Sturmgeschütz* built on the Pz.Kpfw.III chassis amounted to 9409, which was more than the total production of any German tank (1.77).

New designs and improved versions of the existing vehicles developed in response to the appearance of the T-34 and KV not only made German tanks more than a match for the Soviet tanks in terms of gun-power but also put them well ahead of British and US tanks. So far as British tanks were concerned, the 40mm

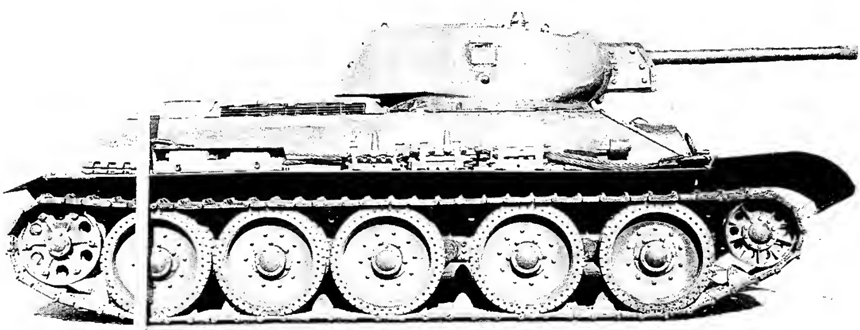


Fig. 1.9 Soviet T-34 medium tank.

guns of the early cruiser tanks, from the Mark I to the Mark VI Crusader, and of the Matilda infantry tank, were superior in terms of armour penetration to the 37mm gun of the original Pz.Kpfw.III and almost equal to its short 50mm gun.

However, no attempt was made in Britain to develop a tank with a larger calibre dual-purpose gun like that of the Pz.Kpfw.IV. What was developed were only close support versions of the cruiser and infantry tanks armed with 76.2mm howitzers, which were limited-purpose weapons with no armour piercing capability and which were in no way comparable to the dual-purpose guns of similar calibre mounted at the time in Soviet as well as German tanks.

A larger, 57mm gun was mounted in 1942 in the Crusader III cruiser tank and Churchill III and IV infantry tanks. Its armour-piercing capabilities were considerably greater than those of the 40mm gun and almost the same as those of the long 75mm with which Pz.Kpfw.IV had been rearmed by then. But it was still inferior to the latter, and other 75 or 76mm guns, so far as high explosive shells were concerned. Moreover, there was no British tank with a more powerful gun that could match the 88mm gun of the Tiger, which had appeared in 1942.

In fact, cruiser and infantry tanks continued to have exactly the same main armament, in spite of the considerable differences in their weight. This meant that the heavier, infantry tanks could not play a role equivalent to that of the heavy tanks of the German and Soviet armies, which were not merely more heavily armoured than the medium tanks but which were also armed with much more powerful guns. As it was, they were never expected to be a more powerfully armed complement to the cruiser tanks. Instead, they were intended to form a separate category of tanks for close cooperation with the infantry and for this purpose they were much more heavily armoured than the cruiser tanks but not more heavily armed. Thus, as a contemporary War Office publication put it, "The main differ-

Fig. 1.10 US M4A1 medium tank.

ence between the infantry and cruiser tanks lies in the thickness of armour" (1.78).

The concentration on armour protection in the development of the infantry tanks paid off at first in the case of the Matilda, which enjoyed a high degree of immunity when it was used in 1940 and 1941 in Africa against ill-equipped Italian forces. But, based as it was on armour protection, its success was cut short, like that of the Soviet KV, by the appearance of more effective anti-tank weapons. Thereafter it had to rely more on its armament and in this respect it was no better than the contemporary cruiser tanks. The same was true of its successor, the Churchill infantry tank, whose armour was progressively increased to a maximum of as much as 152mm but which, in spite of it, did not distinguish itself as a fighting vehicle.

In 1943 it was finally recognised that tank guns should not only be armour-piercing weapons but dual-purpose guns capable of delivering effective high explosive fire as well as perforating the armour of enemy tanks. Thus the final, 40 ton version of the Churchill and the 28 ton Cromwell cruiser tank were both armed with medium velocity 75mm guns. But when these tanks went into action in 1944 their armament was two years behind that of the Pz.Kpfw.IV and three behind that of the T-34. Moreover, they were no longer powerful enough to fight effectively the latest types of the opposing tanks, such as the Panther or, even more, the Tiger.

The official attitude towards this situation was that "the tank is designed with the primary object of destroying or neutralizing enemy unarmoured troops" (1.79). This may have been true during the First World War but the view implied by this statement that tanks should not normally fight enemy tanks was no longer realistic when both sides were using tanks on a large scale and fighting them could not be avoided. Nevertheless, such views persisted and so did the policy, of which they were an expression, of developing and using the two separate categories of infantry and cruiser tanks.

This policy was, in fact, the root cause of the inadequate attention given to the gun-power of British tanks and of their shortcomings during the Second World War. How serious these shortcomings were is indicated by the fact that, in spite of the relatively large number of tanks produced in Britain, in 1943 and 1944 British armoured formations had to be equipped to a large extent with US built tanks. Yet in 1941 British tank output was already considerably higher than the German and at its peak of 8611 in 1942 it was more than double the latter (1.80).

The US tanks with which a number of British as well as the US armoured formations were equipped were principally the M4 Sherman medium tanks. These tanks owed much of their origin to the use by the German armoured forces of the Pz.Kpfw.IV with its 75mm gun, from which the US Army drew the very sensible conclusion that it required a medium tank with a gun of the same calibre (1.81). A month before this conclusion was reached in June 1940, the US Army had only 464 tanks (1.82). What is more, the latest and most powerful of them was the prototype of the M2A1 medium tank, a peculiar 21 ton vehicle with a 37mm gun in a two-man turret and no less than six machine guns in the hull. Two of these were fixed in the front plate for firing forward by the driver and the other four were in small sponsons at each corner of the superstructure, which made the M2A1 almost a throw-back to the original British tanks of 1916. However, the M2A1 had a sound chassis, which could be used as the basis of a new medium tank. In view of the urgent need for it, it was decided that it would take too long to produce a new tank with a 75mm gun mounted in a turret. Instead, the gun was mounted in the

hull, for which a prototype fortuitously existed in the form of the experimental T5E2 medium tank built in 1939. The configuration of the resulting M3 medium tank left a good deal to be desired but it could be produced quickly and it proved effective when first used by British tank units in Libya in 1942.

In the meantime the prototype of a second medium tank, mechanically similar to the M3 but with a turret-mounted 75mm gun, was completed in September 1941 and began to be produced in February 1942 as the Medium Tank M4. By July 1945, when the last of them were built, 49 234 tanks of this type were produced, which almost equalled the total number of T-34 tanks that were produced by then (1.83).

As they were produced, the M4 medium tanks became the principal equipment of the US as well as British and then also of the recreated French armoured formations. Their general layout was similar to that of the Pz.Kpfw.IV and their 75mm guns were comparable to the 76.2mm guns of the T-34 but they were inferior in their armour piercing capability to the long 75mm guns with which Pz.Kpfw.IV was rearmed by the time the M4 appeared in the field in 1942. The M4 only caught up with the Pz.Kpfw.IV in gun power when an improved version was produced at the beginning of 1944 with a long-barrelled 76mm gun. However, by the time the rearmed M4 came into service new German as well as Soviet tanks were already armed with more powerful guns. Nevertheless, a few months before the Anglo-American landings in Normandy in June 1944 it was still considered in the United States that two thirds of the M4 tanks should remain armed with the 75mm gun (1.84). But once the fighting in Normandy started the inadequate performance of the 75mm gun, particularly against the frontal armour of enemy tanks, because too obvious to be ignored.

The complacency which existed until then about the armament of the M4 tanks was largely due to the view held by the command of the US Army Ground Forces that it was not the function of tanks to fight enemy tanks and that the role of armoured formations was one of exploitation and pursuit (1.85). This view resembled the contemporary attitude of the British Army to the role of armoured

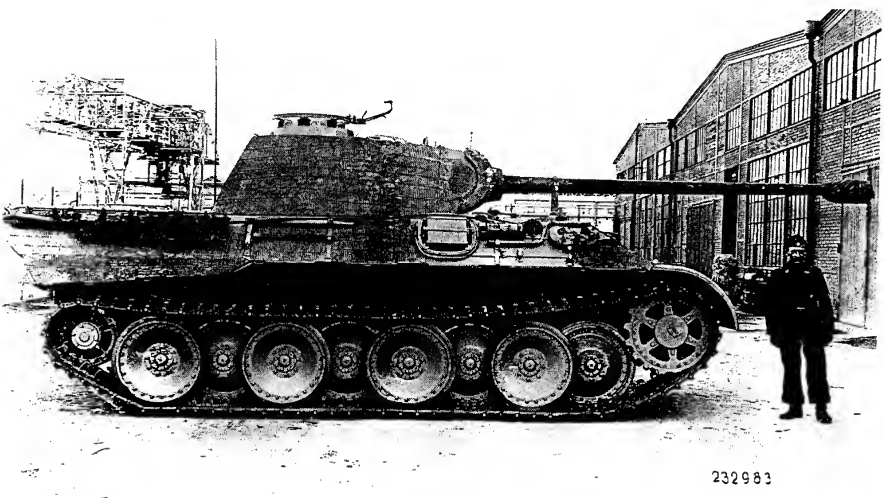


Fig. 1.11 German Panther medium tank.

formations and the damage it caused to the development of US tanks was ensured by the creation of separate units of tank destroyers "especially designed for offensive action against hostile armored forces" (1.86).

The tank destroyers were more heavily armed than the contemporary tanks and in the eyes of the commander of the Army Ground Forces, Lt. General L J McNair and their other proponents, they eliminated, or at least reduced, the need for tanks to be equally heavily armed. This view was an illusion, as tanks still had to fight enemy tanks and therefore needed to be armed for it. In consequence, the attitude of the Army Ground Forces stood in the way of arming tanks with guns sufficiently powerful to fight enemy tanks and the creation of the Tank Destroyer Force caused a dispersion of development effort and of the forces in the field.

Some consideration was given in 1942 and 1943 to arming the M4 with a more powerful, 90mm gun but this possibility was abandoned in 1944 in favour of a new tank, the M26 Pershing. This tank was the outcome of a somewhat diffuse chain of developments which started in 1942 with the design of a new medium T20 tank with a 76mm gun and involved the construction of several other experimental tanks with 76 and then 90mm guns. One of the latter was finally approved in December 1944 and a small pre-production batch of what was to be adopted as the Pershing was sent to Europe to see action shortly before the war ended.

The 41 ton Pershing represented a considerable advance on the M4 mechanically and it was also more heavily armoured and armed with a more powerful 90mm gun. But its armour and armament did not represent any significant advance on the German Tiger I, which was introduced more than two years earlier. Thus at the end of the Second World War, both the US and the British Army were still well behind the German Army in the gun-power of their tanks. But the doctrines which were largely responsible for this had become discredited and it was generally being recognised that tanks must be well armed to fulfil their potential as a mobile source of fire power effective against a wide range of battlefield targets, including enemy tanks.

1.6 References

1.1 A Duvignac, *Histoire de l'Armée Motorisée*. Imprimerie Nationale. Paris. 1948, p.14.

1.2 'The Evolution of the Chain-Track Tractor'. No.II, *The Engineer*, Vol.124. 17 August 1917, p.135.

1.3 R B Gray, *Development of the Agricultural Tractor in the United States*, Part 1. American Society of Agricultural Engineers. St. Joseph. Michigan, 1956, pp.41-43.

1.4 'The Evolution of the Chain-Track Tractor', No.V, *The Engineer*, Vol.124. 7 September 1917, p.202.

1.5 J H A Macdonald. 'Automobiles for War Service', *Cassier's Magazine*, Vol.22, No.6, October 1902, p.676.

1.6 'The Automobile Club Show', *The Engineer*. Vol.87, 23 June 1899, p.627.

1.7 'The Simms Motor War Car', *The Autocar*. Vol.8, 12 April 1902, pp.363-366.

1.8 R M Ogorkiewicz. 'Sixty Years of Armoured Car Development', *The Engineer*, Vol.208, 21 August 1959, pp.96-101.

1.9 A Duvignac, *op.cit.*, pp.160-163.

1.10 *Ibid*, pp.157-159.

1.11 R E Crompton, *Reminiscences*. Constable. London, 1928, p.214.

1.12 F Heigl, *Taschenbuch der Tanks*. Lehmanns Verlag, Munich. 1927, pp.11-13.

1.13 J Milsom. *Russian Tanks 1900-1970*, Arms and Armour Press. London. 1970, p.11.

1.14 B Liddell Hart, *The Tanks*, Cassell, London, 1951, Vol.I, pp.21-25.
1.15 E D Swinton, *Eyewitness*, Hodder and Stoughton, London, 1932, p.10.
1.16 R M Ogorkiewicz, 'The First Tracked Armored Vehicle', *Armor*, Vol.74, No.4, July-August 1965, pp.46-49.
1.17 W S Churchill, *The World Crisis, 1911-1918*, Butterworth, London, 1931, pp.311-312.
1.18 L A Legros, 'Tanks and Chain-Track Artillery'. *The Engineer*, Vol.132, 2 December 1921, pp.592-594.
1.19 M Sueter, *The Evolution of the Tank*, Hutchinson, London, 1937, pp.71-84.
1.20 A G Stern, *Tanks 1914-1918*, Hodder and Stoughton, London, 1919, p.31.
1.21 E D Swinton, *op.cit.*, pp.226-227.
1.22 E H Tennyson d'Eyncourt, 'Account of the British Tanks used in the War', *Engineering*, Vol.108, 12 September 1919, pp.334-339, and 19 September 1919, pp.370-375.
1.23 F J Deygas, *Les Chars d'Assaut*, Charles-Lavauzelle, Paris, 1937, pp.62-69 and 93-196.
1.24 E D Swinton, *op.cit.*, p.198.
1.25 J F C Fuller, *Memoirs of an Unconventional Soldier*, Nicholson and Watson, London, 1936, pp.318-341.
1.26 L Jackson, 'Possibilities of the Next War', *RUSI Journal*, Vol.65, No.457, 1920, pp.71-89.
1.27 A Duvignac, *op.cit.*, p.349.
1.28 R E Jones, G H Rarey and R J Icks, *The Fighting Tanks since 1916*, National Service Publishing Co., Washington, 1933, p.157.
1.29 A Pugnani, *Storia della Motorizzazione Militare Italiana*, Rogero & Tortia, Turin, 1951, p.184.
1.30 G Ferre, *Le Defaut de l'Armure*, Charles-Lavauzelle, Paris, 1948, pp.34-46.
1.31 J F C Fuller, *op.cit.*, pp.408-410.
1.32 J F C Fuller, *ibid.*, p.405.
1.33 G le Q Martel, *Our Armoured Forces*, Faber and Faber, London, 1945, pp.396-402.
1.34 J F C Fuller, *Armoured Warfare*, Eyre and Spottiswoode, London, 1943, p.27.
1.35 G T Denison, *A History of Cavalry*, Macmillan, London, 1877, pp.457-461 and 470-474.
1.36 *The Co-operation of Tanks with Infantry Divisions*, Military Training Pamphlet No.63, The War Office, London, 1944, p.6.
1.37 G Ferre, *op.cit.*, p.30.
1.38 *The German Armored Division*, Military Intelligence Service Bulletin No.18, War Department, Washington, 1942.
1.39 F J Deygas, *op.cit.*, pp.338-340.
1.40 B H Liddell Hart, 'The Development of a New Model Army,' *Army Quarterly*, Vol.9, No.3, October 1924, pp.37-50.
1.41 C de Gaulle, *Vers l'Armée de Metier*, Berger-Levrault, Paris, 1934.
1.42 L von Eimannsberger, *Der Kampfwagenkrieg*, Lehmanns Verlag, Munich, 1935.
1.43 F J Deygas, *op.cit.*, pp.197-221.
1.44 R E Jones, et.al., *op.cit.*, pp.140-142.
1.45 A Duvignac, *op.cit.*, pp.352-353 and 439-449.
1.46 D Crow, ed., *AFVs of World War One*, Profile Publications, Windsor, 1970, pp.103-108.
1.47 D Crow, ed., *British AFVs 1919-40*, Profile Publications, Windsor, 1970, pp.2-8.
1.48 G le Q Martel, *In the Wake of the Tank*, Sifton Praed, London, 1931, pp.110-122.
1.49 B Pafi, C Falesi and G Fiore, *Corazzati Italiani 1939-45*, D'Anna Editore, Rome, 1968, pp.65.67.
1.50 D Crow, ed., *op.cit.*, pp.25-44.

1.51 M M Postan, *British War Production*, HMSO, London, 1952, p.186.
1.52 D Crow, ed., *ibid.*, pp.13-20.
1.53 W Esser, *Dokumentation über die Entwicklung und Erprobung der ersten Panzerkampfwagen der Reichswehr*, Krauss-Maffei, Munich, c.1979.
1.54 T Hara, *Japanese Medium Tanks*, AFV/Weapons Profiles, No.49, Profile Publications, Windsor, 1972.
1.55 W Esser, *op.cit.*, pp.50-51 and Appendix 5.
1.56 D Crow, ed., *op.cit.*, pp.21.24.
1.57 G le Q Martel, *op.cit.*, pp.42 and 205.
1.58 H Guderian, *Panzer Leader*, Michael Joseph, London, 1952, pp.27-28.
1.59 W Esser, *ibid.*, pp.38-47.
1.60 R E Jones, *et al.*, p.168.
1.61 G F Hofmann, 'A Yankee Inventor and the Military Establishment: the Christie Tank Controversy', *Military Affairs*, Vol.39, No.1, February 1975, pp.12-18.
1.62 G le Q Martel, *An Outspoken Soldier*, Sifton Praed, London, 1949, pp.127-129.
1.63 G le Q Martel, *Our Armoured Forces, op.cit.*, p.19.
1.64 R Jacomet, *L'Armement de la France 1936-1939*, Editions Lajeunesse, Paris, 1945, p.288 and 291.
1.65 G Ferre, *op.cit.*, pp.127-140.
1.66 B Mueller-Hillebrand, data dated 21 December 1952 based on records of Oberkommando des Heeres (OKH).
1.67 H Guderian, *op.cit.*, pp.472.
1.68 *The German Campaign in Russia – Planning and Operations (1940-1942)*, Department of the Army Pamphlet No.20-261a, Washington, 1955, p.41.
1.69 J Magnuski, *Wozy Bojowe 1914-1964*, Ministry of Defence, Warsaw, 1964, p.131.
1.70 M Parrish, 'The Soviet Mechanized Corps in 1941', *Armor*, Vol.92, No.6, November-December 1983, pp.19-22.
1.71 R L Garthoff, *Soviet Military Doctrine*, Free Press, Glencoe, Illinois, 1953, pp.431 and 504.
1.72 J Magnuski, *op.cit.*, p.131.
1.73 J Magnuski, 'Najslynniejszy Czolg II Wojny Światowej', (part 12) *Za Wolność i Lud*, weekly published in Warsaw, c.1976.
1.74 J Magnuski, *Wozy Bojowe LWP 1943-1983*, Ministry of Defence, Warsaw, 1985, p.139.
1.75 P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978, p.261.
1.76 H Guderian, *ibid.*, p.27.
1.77 P Chamberlain et al., *op.cit.*, p.261.
1.78 *The Co-operation of Tanks with Infantry Divisions*, op.cit., p.6.
1.79 *Ibid*, p.9.
1.80 Central Statistical Office, Statistical Digest of the War, HMSO, London, 1951, Table 126.
1.81 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, pp.45-46.
1.82 H W Baldwin, *Defence of the Western World*, Hutchinson, London, c.1941, p.287.
1.83 R P Hunnicutt, *op.cit.*, p.525.
1.84 C M Bailey, 'Tank Destroyers', *Armor*, Vol.88, No.4, July-August 1979, p.11.
1.85 R P Hunnicutt, *ibid.*, p.212.
1.86 *FM 18-5 Tank Destroyer Field Manual*, US Government Printing Office, Washington, 1942, p.7.

1.7 Selected Bibliography

(excluding works already listed under References)

Fire and Movement, RAC Tank Museum, Bovington Camp, 1975.

Illustrated Record of German Army Equipment, Vol.III (Armoured Fighting Vehicles), War Office, London, 1947.
B Bond, *British Military Policy between the Two World Wars*, Clarendon Press, Oxford, 1980.
P Chamberlain and C Ellis, *British and American Tanks of World War II*, Arms and Armour Press, London, 1969.
- *Pictorial History of Tanks of the World 1915-1945*, Arms and Armour Press, London, 1972.
D Crow, ed., *British and Commonwealth AFVs 1940-46*, Profile Publications, Windsor, 1971.
- *American AFVs of World War II*, Profile Publications, Windsor, 1972.
- *German AFVs of World War II*, Profile Publications, Windsor, 1973.
J F C Fuller, *Tanks in the Great War*, John Murray, London, 1920
O H Hacker, R J Icks, O Merker and G P von Zezschwitz, *Heigl's Taschenbuch der Tanks*, Vol.I and II, Lehmanns Verlag, Munich, 1935.
F Heigl, *Taschenbuch der Tanks*, Lehmanns Verlag, Munich, 1926.
R P Hunnicutt, *Pershing*, Feist Publications, Berkeley, 1971.
R J Icks, *Tanks and Armored Vehicles*, Duell, Sloane and Pearce, New York, 1945.
B H Liddell Hart, *The Tanks*, Vol.II, Cassell, London, 1959.
R M Ogorkiewicz, *Armour*, Stevens, London, 1960.
S Pugh, ed., *Armour in Profile*, Profile Publications, Leatherhead, 1968.
F M von Senger und Etterlin, *Die Deutschen Panzer 1926-1945*, Lehmanns Verlag, Munich, 1965.
- *Kampfpanzer* 1916-1966, Lehmanns Verlag, Munich, 1966.
P Touzin, *Les Vehicules Blindés Français 1900-1944*, Editions EPA, 1979.
B T White, *British Tanks and Fighting Vehicles 1914-1944*, Ian Allan, London, 1970.
- *Tanks and Other Armoured Fighting Vehicles 1900-1918*, Blandford Press, London, 1970.
G P von Zezschwitz, *Heigl's Taschenbuch der Tanks*, Vol.III, Lehmanns Verlag, Munich, 1938.

Chapter 2

Development of Tanks since 1945

2.1 General Trend

When the Second World War came to an end in 1945 tank development became confined, for all intents and purposes, to four countries: the Soviet Union, the United States, Britain and France. In many respects the Soviet Union dominated the post-war tank scene as it maintained by far the largest armoured forces. Moreover, its armoured forces were not only large but, as in the latter stages of the war, they formed the main striking force of the Soviet Army, which forced other armies to pay particular attention to them.

As elsewhere, the appearance of new anti-tank weapons led to some discussion within the Soviet Army about the future of tanks but their continued importance was upheld and the number of armoured formations was increased both in relative and absolute terms. Thus, of the total of 175 divisions which NATO estimated the Soviet Army to have as a result of its post-war reorganisation, 65 were tank and mechanised divisions (2.1). What is more, out of the 22 divisions which were stationed in East Germany and which were brought up to a high state of readiness in 1950, 18 were tank or mechanised divisions. At the time each tank and mechanised division had about 250 and 200 medium and heavy tanks respectively, and the 18 divisions with their total of some 4000 tanks constituted the striking force of the Soviet Army in Central Europe.

In contrast, the US Army reduced its armoured forces to only one division out of the ten regular divisions it was left with in 1948. This lone armoured division apart, US tanks were dispersed among the divisional tank battalions and regimental tank companies of the infantry divisions, which amounted to a return to the pre-war policies of confining most tanks to infantry support. The only progress that was made was the acceptance of the fact that tanks had to be armed well enough to fight enemy tanks (2.2). This put an end to the policy pursued to the detriment of US tank development by the Army Ground Forces and to its concomitant, the Tank Destroyer Command, which was finally disbanded after the war.

The decline of the US armoured forces immediately after the war was accompanied by widespread doubts about the future of tanks, which arose due to the development of anti-tank weapons. In particular, newly introduced infantry anti-tank weapons such as the US bazooka rocket launcher, the German *Panzerfaust* and recoilless rifles were considered to make tanks obsolete. It was only when the North Korean forces sucessfully used Soviet-built tanks to invade South Korea in 1950 that doubts about the future of tanks were dispelled. In consequence, the US

Army raised a second armoured division in 1951 and accelerated the development of new tanks.

The position of tanks and of armoured units in general was strengthened shortly afterwards by the prospect of the tactical use of nuclear weapons, which began to be explored in 1951 in a series of tests carried out in the Nevada desert. As a result, armoured units came to be considered better able than others to operate on what was then called the 'atomic battlefield' because of their mobility and of the protection provided by their armour. Their ability to operate in conjunction with tactical nuclear weapons was demonstrated in 1955 when a tank battalion carried out for the first time a simulated exploitation of a nuclear explosion at the Nevada test site (2.3).

A similar attitude was adopted in the Soviet Union and was reflected in a 1962 statement by the leading Soviet authority on armoured warfare, Marshal P Rotmistrov: "In a nuclear war, should one break out, tanks will occupy the dominant position on the battlefield" (2.4).

In the meantime the US Army increased the number of its armoured divisions to four. During the 1960s there was also a shift of emphasis from nuclear weapons back to conventional forces as a result of the onset of strategic parity between the United States and the Soviet Union. In view of this and the fact that the armoured forces of the United States and its allies continued to be numerically inferior to those of the Soviet Union, the US Army made a major effort to gain qualitative superiority by developing in collaboration with the German Army a 'revolutionary new tank', which was designated MBT-70 (2.5). However, the MBT-70 programme proved to be over-ambitious and was terminated in 1971 by the US Congress on grounds of excessive cost. In consequence, the US Army embarked in 1972 on the development of a more conventional tank, the XM-1.

The controversy surrounding the MBT-70 obscured a significant change that had taken place at the time in US Army policy in favour of a single type of battle tank. The MBT-70 embodied it and moves towards it had already resulted in the withdrawal from service in 1964 of US heavy tanks. The Soviet Army retained its heavy tanks for several more years and they formed part of the Soviet forces which invaded Czechoslovakia in 1968. But during the 1970s the Soviet Army also concentrated on a single type of battle tank, as did other armies.

A policy of concentration on a single type of battle tank was eminently sensible because no other tank could be superior to it and, therefore, could be justified if the tank on which development concentrated was already as good as it could be as a battle tank. Other types of tanks could always be designed, of course, for different, special roles but they were bound to be inferior, overall, to the more versatile battle tanks designed to defeat the widest possible range of battlefield targets, including enemy tanks.

An extreme example of tanks designed for such special roles were the infantry and cruiser tanks which the British Army employed right up to the end of the Second World War in spite of their serious deficiencies. However, in 1944 while British troops were still fighting in Normandy, their commander, General Montgomery, proposed the abolition of the division between infantry and cruiser tanks and the adoption instead of a single type of 'capital' tank. As it happens, the latter was eventually developed into a heavy gun tank, which was used in small numbers between 1955 and 1966. But in the meantime the policy of using a single type of battle tank was put into effect with the adoption as such of the Centurion tank in 1949 (2.6).

The French Army decided even earlier than the British to concentrate on a

single type of battle tank. In fact, such a tank began to be considered even before the war ended and was developed as part of the French Army's post-war re-equipment programme. However, its development did not proceed beyond a number of prototypes and was abandoned in the mid-1950s when the French Army turned its attention to another and lighter type of battle tank. The latter stemmed from an agreement reached in 1957 with Germany to produce a common 'European' tank although, eventually, each country adopted its own design. But the French AMX-30 and the German Leopard retained at least one feature in common in being less heavily armoured than other contemporary tanks such as the British Chieftain and, to a lesser extent, the US M60 tank. In this respect their design reflected the view, which had become widespread, that heavy armour was no longer as valuable as it had been because of progress in the development of anti-tank guided missiles and other weapons with shaped charge warheads that could perforate the thickest tank armour.

The armour piercing capabilities of anti-tank guided missiles also led to claims during the 1960s and early 1970s that they were making tanks obsolete. Similar claims had been made before, when other anti-tank weapons first appeared and they ignored, once again, the fact that tanks had never been invulnerable and that armour protection was not their only or even principal attribute. Nevertheless, infantry anti-tank guided missiles were widely acclaimed as 'tank killers'. In part this was due to them being produced by the aerospace industry which has been much more articulate and aggressive in promoting its products than those concerned with tanks.

Further claims that tanks were becoming obsolete were then made on account of the development of missile-carrying helicopters. They were encouraged by the very first use of helicopters against tanks by the US Army which occurred in 1972 at Kontum during the closing stages of the war in Vietnam: it was highly successful but its scale was very limited (2.7). A broader basis for the claims made for helicopters was provided by the results of trials and in particular of a US-German-Canadian trial carried out in 1972 in Germany at Ansbach in which an average of 18 tanks was adjudged to be 'killed' for each helicopter 'kill' (2.8). The results of this trial were widely advertised at the time but little was said about its scenario, which favoured helicopters.

Claims made for anti-tank guided missiles reached their climax at the beginning of the Arab-Israeli war of 1973, when Egyptian infantry armed with Soviet-made 'Sagger' missiles repulsed the initial counter-attacks of Israeli tank units with heavy losses. The immediate reaction of many people to this was "time was running out for the tank" (2.9). But, although the Israeli units which were involved lost a high proportion of their strength, the number of tanks they actually had was relatively small (2.10). Many more tanks were subsequently lost by both sides to the guns of the opposing tanks, which showed that the claims made for the relative effectiveness of anti-tank guided missiles on the basis of the initial engagements along the Suez Canal were greatly exaggerated. The losses inflicted by their guns also demonstrated how effective tanks continued to be.

After 1973 infantry anti-tank guided missiles were viewed somewhat more objectively. In particular, their limitations as well as their capabilities were noted and they were seen to have limited battlefield mobility as well as being vulnerable to suppressive fire. Moreover, the smaller missiles were rendered far less effective by the development of new types of armour which were almost three times as effective in relation to their weight as conventional, homogeneous steel armour. The new type of armour was first successfully developed in Britain and soon after

its appearance it was adopted, in 1972, for the US XM-1 tank which was described in 1976 by the US Secretary of the Army as "impervious to any currently known anti-tank missile" (2.11).

Guided missiles could always be made large enough, of course, to destroy any tank. But if they were large they were no longer portable infantry weapons and would have to be mounted in armoured vehicles to have any reasonable degree of battlefield mobility. These vehicles could include battle tanks and a gun-cum-missile launcher actually formed the main armament of the US-German MBT-70, as well as one or two other tanks developed during the 1960s. However, by 1972 it was generally recognised that guns were superior. after all, to guided missile systems as tank armament.

The position of guns in relation to guided missiles was greatly strengthened by two developments during the late 1960s and early 1970s. One was the development of armour-piercing, fin-stabilised, discarding-sabot (APFSDS) projectiles with long-rod penetrators that could perforate considerably thicker armour than the earlier types of kinetic energy armour-piercing projectiles. The other important development was that of fire control systems with laser rangefinders and electronic ballistic computers, which increased considerably the hit probability of tank guns, particularly at longer ranges.

All this led during the 1970s and 1980s to the development of a new generation of battle tanks, which came to have similar features, including much more effective. multi-layered armour and guns of 120 or 125mm. What is more, tanks came to be generally accepted as a versatile, mobile source of fire power effective against a wide range of battlefield targets, including enemy tanks.

However. there is still a tendency to define tanks as offensive weapons or, even more narrowly, as assault vehicles and to ignore or to reject their defensive capabilities. This is done in spite of the fact that gun-carrying armoured vehicles such as tanks are no more 'offensive' or 'defensive' than a soldier with a rifle is 'offensive' or 'defensive'. There is, therefore, no fundamental reason why tanks should not be employed defensively as well as offensively and there are many examples of their successful employment on the defence. These range from the defensive battle successfully fought in 1944 by the Grossdeutschland Panzer Division at Targul Frumos in Romania to the successful defence in 1973 of the Golan Heights by the 7th Armoured Brigade of the Israeli Army (2.12).

2.2 Soviet Tanks

Of the four countries to which tank development was confined after the Second World War. the Soviet Union maintained the highest degree of continuity. Thus, the post-war tanks of the Soviet Army were, in essence, direct developments of its well-proven war-time tanks, the T-34-85 medium tank and the IS-2, or Stalin, heavy tank. Both had been introduced in 1944 and remained in service for many years after the war. But even before the war ended in 1945 a successor appeared to each of them.

The successor to the IS-2 was the IS-3, a heavy tank having virtually the same general characteristics, 46 ton weight and 122mm D-25T gun as its forerunner. But its hull and turret were much better profiled and the turret armour was also thicker. which implied a considerably higher degree of ballistic protection. However. its good protection and its commendably low silhouette were achieved at the expense of a cramped fighting compartment and an ammunition load of only 25 or. at most. 28 rounds (2.13). Nevertheless, the IS-3 was generally regarded to be a

formidable tank and was responsible to a large extent for the development, as a counter to it, of other heavy tanks.

The IS-3 remained in service with the Soviet Army until the late 1960s and was used by the Egyptian Army during the Arab-Israeli war of 1967, although without any particular success. By then its place in the Soviet Army had been largely taken by its enlarged version, the T-10 heavy tank, which was introduced during the 1950s and remained in service until the early 1970s. The T-10 was less important than the IS-3 had been because by the time it was put into service its main armament was not more effective than that of contemporary Soviet medium tanks and the only relative advantage it had was thicker armour.

The second of the Soviet tanks introduced before the end of the war was the T-44 medium tank. This 32 ton tank was to be a successor to the T-34-85, of which it was a development. It differed from the latter in following the example of the heavy tanks, like the IS-2, in having a four, instead of a five, man crew and torsion bars instead of the coil springs inherited by the T-34 tanks from Christie's designs. It also had its engine mounted transversely, which saved space within the hull by comparison with the longitudinal location of engines, which had been used until then in Soviet tanks and is still used in almost all others. But, although its turret was somewhat different, its main armament was the same 85mm ZiS-S-53 gun as that of the T-34-85. It did not, therefore, represent an advance on the latter so far as the most important aspect of tanks is concerned. It is not surprising, therefore, that the production of the T-44 was abandoned around 1949 after a relatively short run in favour of another medium tank, the T-54.

The 36 ton T-54 had basically the same chassis as the T-44 but its turret was larger and mounted a 100mm D-10T gun. The design of the latter was based on that of a naval gun and it had been mounted since 1944 in the SU-100 turretless assault gun. The installation of this gun in the T-54 gave it a main armament as effective as that of the IS-3 and by so doing paved the way for the eventual

Fig. 2.1 Soviet T-34-85 medium tank. (R. Fleming)

disappearance of Soviet heavy tanks.

In contrast to the decreasing use of the heavy tanks, the T-54 was used on an increasing scale and became the most numerous tank in the world. A prototype of it was built as early as 1945 and it began to be produced in 1948, with the result that by the late 1950s it had largely replaced the earlier types of medium tanks in the Soviet tank units. The T-54 was also produced in Poland from 1956 to 1964, in Czechoslovakia and in China as the Type 59 tank (2.14).

In addition to the countries which produced them, the T-54 and its improved T-55 version have also been used in many others to which they were exported during the 1960s and 1970s. In particular, they were exported in large numbers to several Arab countries and also to others ranging from Finland to India, Peru and Angola while their Chinese equivalent, the Type 59, was exported in quantity to Pakistan.

In the meantime, during the late 1950s and early 1960s, the Soviet Army developed a new, medium tank, the T-62. This tank had much the same chassis as the T-55, although its hull was somewhat longer, but it was armed with a more powerful 115mm U-5T smooth-bore gun mounted in a new, larger diameter turret. The development of the 115mm U-5T gun and its APFSDS ammunition is believed to have been inspired by the work carried out in Germany during the Second World War on fin-stabilised 'arrow' projectiles, although for long-range artillery and anti-aircraft guns rather than tank guns (2.15). It also happened to be pursued at the same time as work in the United States on smooth-bore tank guns. But in 1957 the US Army decided to switch its efforts to guided missile systems and to curtail work on high velocity guns (2.16). The Soviet Army proved wiser by continuing its development of smooth-bore tank guns and, with the introduction of the T-62 in the early 1960s, became the first to put into service a tank armed with this type of gun.

The T-62 was supplied to Syria and Egypt, both of which used it during the 1973

Fig. 2.2 Soviet T-55 tank. (R. Fleming)

Arab-Israeli war, and to Iraq, Libya and Cuba. Otherwise its use was confined to the Soviet Army. In consequence, when it came to acquiring tanks more modern than the T-54 or T-55, several armies which had come to depend on the Soviet Union for their tanks obtained during the late 1970s and the 1980s the next Soviet tank, the T-72. In particular, the T-72 was supplied to Syria, which used it during the fighting in Lebanon in 1982, as well as Algeria, Iraq and Libya and also to other countries, including India, Yugoslavia, Poland and Czechoslovakia, all four of which have since produced it under licence.

The T-72 was preceded by a very similar medium tank, the T-64, which was developed during the 1960s but which was produced on a much smaller scale and issued only to Soviet tank units. Like the T-62, the T-64 and the T-72 are armed with smooth-bore guns but of a large 125mm calibre and, therefore, with greater armour piercing capability. Moreover, they are the first turreted tank to enter service with automatic loading systems for their guns. As a result, their crews consist of only three, instead of four men and, in spite of their more powerful guns, their silhouette is as low as that of the earlier tanks. Their low height also made it possible to provide them with thicker armour within a relatively low vehicle weight, which in the case of the T-72 is 41 tons. Like all other Soviet tanks built since 1945, the T-72 has a torsion bar suspension and is powered by a transversely mounted engine, which is basically the same 38.8dm^3 V-12 diesel as that introduced in 1939 in the BT-7M and used to power all Soviet medium and heavy tanks from the T-34 and KV onwards. Unlike the earlier models of this engine, the V-46 version is supercharged and has a considerably higher output of 780hp (537.7kW). Its use and that of the earlier versions over a period of 40 years has saved the Soviet Union a great deal of effort by comparison with that spent, or misspent, during the same period in other countries on the development of several different engines.

In addition to the medium and heavy tanks, the Soviet Army also developed a light tank, the 14 ton PT-76, which entered service around 1952. It was as large as the medium tanks but its armour was thin and its medium-velocity 76.2mm gun had long ceased to be effective against enemy tanks. Its value as a fighting vehicle was very limited therefore, although in this respect it was not different from other light tanks. However, it was only designed to be a reconnaissance vehicle and as such it had the merit of being amphibious. Its large size gave it sufficient buoyancy to swim across inland waters with little if any preparation and it was the first tank to be fitted with water jet propulsion units, which gave it a speed in water of up to 10km/h.

Following its adoption by the Soviet Army, the use of the PT-76 spread to many countries, including Vietnam, but its production came to an end in the late 1960s. Since then the production of tanks in the Soviet Union has been generally estimated to average about 3000 vehicles per annum. As a result, the Soviet Union has continued to have more tanks than any other country in the world. During the 1950s its stock of tanks was generally estimated at about 35 000, although some contemporary estimates put it at twice this figure (2.17, 2.18). More recent estimates put it at 52 000 tanks and in 1989 the Soviet Union itself admitted to having 59 470 tanks (2.19, 2.20).

2.3 British Tanks

In contrast to the continuity in the development of the Soviet tanks, that of British tanks experienced a major change in direction after the end of the Second World

War. Until then the British Army continued to adhere to the pre-war policy of two separate categories of infantry and cruiser tanks. After 1942 attempts were made to rationalise their production by the use of common components but there were still two types of tanks which differed from each other in the amount of armour and weight but not in what mattered most, namely the main armament. The final outcome of this was the A.41 'heavy cruiser', six prototypes of which were completed just as the war ended in Europe. Its engine and transmission were much the same as those of the earlier Cromwell and Comet cruiser tanks and its Horstmann bogie-type suspension was inferior to the earlier cruisers' Christie-type independent suspensions. But its 76.2mm 17 pounder gun represented a significant advance in the main armament of the cruiser tanks and its armour protection was also considerably better. The latter included, at last, a single sloping glacis plate. The design of the A.41 also very sensibly dispensed with the hull machine gunner, so that it had a crew of four men, which was to become general practice.

The A.41's main armament, armour and general characteristics put it on a par with the German Panther and it was deservedly produced and put into service in 1946 as the Centurion medium tank.

In 1946 the British Army also decided at long last to abandon the policy of having infantry and cruiser tanks, which did so much harm to the development of tanks in Britain, and adopted instead the concept of a 'universal' tank. Unfortunately, this concept implied not only a single type of battle tank but also one which could be readily adapted to a wide variety of special roles such as flame-throwing, mine flailing, bridge-laying and bulldozing, and which would also be capable of swimming with the aid of a collapsible flotation screen. The requirement that the universal tank be adaptable to all these roles grew out of the attention which the British Army came to devote during the war to various special-purpose versions of tanks. This led to the development of several ingenious devices but it also diverted attention and effort from the basic type of gun tank. How large a proportion of the available resources was devoted to the special-purpose versions of tanks is indicated by the fact that in the closing stages of the war they accounted for a special armoured division, the 79th, when the British Army only had a total of four other, normal armoured divisions.

The range of roles to which the universal tank was to be adaptable and the armour which it was expected to have were beyond the capabilities of the Centurion. In consequence, the design of the universal tank, or FV 201, was based on that of the A.45, which was originally proposed in 1944 as the infantry tank companion of the A.41 Centurion when the latter was still considered to be a cruiser tank. But, when the first prototype was completed towards the end of 1948, the FV 201 was considered too costly to produce as well as being unduly large and heavy, although even then it was not adaptable to all the special roles that were envisaged. Its development was therefore cancelled in 1949 and the British Army decided to retain as its basic tank the Centurion, which by then weighed 49 tons and was armed with the same 83.8mm 20 pounder gun as that proposed for the FV 201.

However, it was decided almost simultaneously that an even more powerful gun was needed to counter the Soviet IS-3 heavy tank. The only suitable gun available was one of 120mm developed in the United States but it was too big to be mounted in the Centurion. In consequence it was decided to mount it in a new tank which would use the chassis of the FV 201 and which, as a heavy tank with a 120mm gun, also fitted an agreement reached in 1948 between Britain, the United States and Canada that there should be a heavy tank in addition to a medium and a light

tank.

The new tank, which was designated FV 214 and called Conqueror, weighed 65 tons and was powered by an up-rated, fuel-injection version of the V-12 Meteor gasoline engine used in the Centurion. It also had the same type of transmission as the Centurion and a modified form of the latter's Horstmann suspension. Like the Soviet IS-3, it had to have separated ammunition for its gun and, in spite of its large size, it did not carry very many more rounds – 35, in fact.

The first prototype of it was ready in 1952 and it began to enter service in 1956. However, only about 180 Conquerors were produced and they were distributed among the armoured regiments of the British Army, which were equipped with the Centurions, as long-range destroyers of heavy tanks, until they were withdrawn from service in 1966.

The need for the Conquerors had in fact begun to disappear soon after they were introduced because of the development of a more powerful, 105mm gun for the Centurion. The new L7 gun was basically a bored-out version of the Centurion's earlier 83.8mm gun but its armour piercing performance was virtually as good as that of the 120mm gun of the Conqueror. In consequence, as the Centurions rearmed with the 105mm L7 began to come into service in 1959, the Conqueror became superfluous while the effectiveness of the Centurions was extended for many more years.

The Centurions had already proved very effective during the war in Korea, where they were first used in 1951, and their effectiveness led to them being adopted not only by the British Army but from the mid-1950s onwards also by several others. They were purchased in 1953-1955 by the Swedish and Swiss Armies and they were also delivered, under US Military Aid Programmes, to Denmark and the Netherlands. Subsequently they were also acquired by Israel, which used them with considerable success during the Arab-Israeli wars of 1967

Fig. 2.3 British Centurion with 83.8mm gun. (Ministry of Defence, Crown Copyright Reserved)

and 1973, as did the Indian Army during the Indo-Pakistani war of 1965. In fact, the Centurion became one of the most widely used tanks and the most successful, due primarily to the performance of its 83.8 and 105mm guns.

Production of the Centurions ceased in 1962, by which time 4423 had been built (2.21). The last Centurion was officially withdrawn from service with the Royal Armoured Corps in 1974 but others continued to be used by several armies and in 1982 Centurions were again successfully employed by Israeli armoured units during the fighting in Lebanon.

It is interesting to note that the final British Army version of the Centurion, the Mark 13, which was not only armed with the 105mm L7A2 gun but which was also up-armoured and incorporated various other improvements, weighed 51.8 tons, compared with 42 tons of the original, A.41 prototype armed with the 76.2mm 17 pounder gun.

While the British Army was still equipping itself with Centurions armed with the 83.8mm gun, work started on a successor to them, the FV 4201. Design of it began in earnest in 1958 and the first prototype was built in 1959. Six other prototypes and a pre-production series of 40 followed between 1961 and 1963, when the FV 4201 or Chieftain, battle tank was accepted for service. An order was then also placed for the production of 770 and in 1966 the first Chieftains entered service with British tank units.

At the time of its introduction into service the Chieftain was the most powerfully armed and the most heavily armoured battle tank. Its main armament consisted of a new, 120mm L11 rifled gun, which fired separated ammunition with fully combustible bagged propellant charges. Its armour was significantly thicker than that of the Centurion and it incorporated such novel features as a supine driver's

Fig. 2.4 Prototype of British Chieftain tank. (FVRDE, Crown Copyright Reserved)

position, which made it possible to reduce the height of the hull. It also had a new 'hot-shift' epicyclic gearbox. However, its suspension was of much the same Horstmann type as that of the Centurion and its automotive characteristics were marred by the poor performance of its L-60 two-stroke diesel. The latter was specially developed for it as an engine ideally suited, in theory, to meet the contemporary demand for multi-fuel engines because of its opposed piston configuration. But this configuration also made the L-60 inherently troublesome – a fact ignored when the decision was taken to adopt it.

Depending on the model, the Chieftain weighed between 54 and 56 tons, which was not much more than the final version of the Centurion. Nevertheless, it was criticised at the time of its introduction as being unduly heavy and was compared unfavourably in this respect with the lighter battle tanks being developed in Germany and France. However, the lighter weight of the German and French tanks implied less armour protection and, although no amount of armour could make a tank immune to the anti-tank guided missiles which were then coming into use, the Arab-Israeli war of 1967 demonstrated that heavy armour was still worth having.

Armour became worth having even more with the advent of new, multi-layered types of it, which were at least twice as effective against the shaped charge warheads of missiles, or projectiles, as homogeneous steel armour of the same weight. The lead in the development of the new type of armour was taken in Britain, at the Military Vehicles and Engineering Establishment, and what was developed was called after its location, Chobham armour.

By 1971 the development of Chobham armour had advanced to the stage where it was incorporated in an experimental tank, based on Chieftain components, called FV 4211. The construction of FV 4211 coincided with the commencement of the US M1 tank programme and following its example Chobham armour was incorporated in the design of the prototype of the M1, under Anglo-American exchange of information agreements. However, FV 4211 did not lead immediately to the development of a new, Chobham-armoured tank for the British Army. The reason for it was a decision taken in 1972 by the governments of the United Kingdom and of the Federal Republic of Germany to develop a single battle tank for their armies. The decision was taken for political and financial reasons and it delayed the development of a new tank for the British Army by the time taken to explore the wide range of options proposed in Britain and in Germany. In the end the two countries failed to agree to adopt any one of the designs. In consequence the joint programme was terminated in 1976, when almost all it had done was to waste a lot of time and money, like several other attempts at international standardisation.

Following the collapse of the Anglo-German programme, work started in 1977 on a new, purely British tank called MBT-80. In essence, MBT-80 was a development of FV 4211, which was built six years earlier. But, instead of being based on Chieftain components, it incorporated a completely new engine, transmission and other newly developed components. However, by 1980 it became evident that, because of the time required to develop it, MBT-80 could not be made available to British tank units until the 1990s and that the cost of developing it would be considerable. At the same time the threat posed by the deployment of new Soviet tanks made the production of a new tank for the British Army more urgent. As a result the development of MBT-80 was discontinued in 1980. In its place the British Army decided to develop another tank which could be produced more quickly and which came to be called Challenger.

The reason why the Challenger could be produced more quickly than MBT-80 is that it was based on yet another tank, of which several prototypes had been built by 1979 and production of which had already been planned. All this was done to the requirement of the Imperial Iranian Army for new tanks to follow the 700 Chieftains it ordered from Britain in 1971.

The Iranian requirement led, in fact, to the development of two new tanks. The first of them was FV 4030/2, or Shir 1, which was basically a Chieftain with a new engine and a new transmission, as well as other improvements. The second tank was the FV 4030/3, or Shir 2, which was in effect FV 4030/2 with Chobham armour. Iran ordered both tanks in 1974 but none had been delivered when the government of the Shah was overthrown in 1979 and the order was cancelled.

However. FV 4030/2 was taken up soon afterwards by Jordan, which ordered 274 and put them into service as the Khalid battle tank. On the other hand, prototypes of FV 4030/3 were taken over by the British Army and became the basis of the Challenger. The original production order covered 243 tanks, which began to be delivered to the Army in 1983. Further orders raised the total of Challengers produced for the British Army to more than 400, or enough to equip seven armoured regiments.

Although FV 4030/3 was designed to an Iranian requirement, it was in the mainstream of British tank development and in several respects it was similar to what the MBT-80 would have been had it been built. In essence, FV 4030/3 was a direct development of the Chieftain and so, therefore, is the Challenger. Compared with the Chieftain, the Challenger enjoys the advantage of a much more powerful engine, a more modern transmission, a greatly superior, hydropneumatic suspension and very much more effective Chobham armour protection. However, at 62 tons it is not only heavier than any contemporary battle tank but is also significantly larger. Moreover, it represents no improvement on the Chieftain in the most important respect of all, which is the main armament. Thus, it is armed with the same 120mm L11 gun as that originally developed for the Chieftain in the 1950s. The retention of this gun made the Challenger lag behind the leading tanks of its generation in terms of the main armament but no move was made to provide it with a more powerful gun until 1988, when development began of Challenger 2, which was designed to mount a new 120mm L30 gun.

2.4 French Tanks

When the development of tanks was resumed in France in 1944, it was inevitable that some of it would be a continuation of what was being done when it was stopped by the defeat of 1940. This was the case with the ARL 44 tank, the design of which stemmed from clandestine studies carried out under the German occupation and the first prototype of which was built with commendable speed in 1946. The 48 ton ARL 44 was armed with a high velocity 90mm gun which made it comparable in this respect with other contemporary tanks. But otherwise it was inferior to them. For instance, its running gear, which resembled that of the Char B of 1940, was obsolete by the standards of the late 1940s. Nevertheless, 60 were built by 1950 as *Chars de transition* but they were withdrawn from service after a relatively short time.

What was clearly needed was a fresh start and this was made even before the Second World War ended when studies began of a new battle tank. This tank was developed as part of the French Army's post-war re-equipment programme which called for only one type of battle tank, in contrast to the contemporary policies of

British, United States and Soviet Armies, which were still developing the two categories of medium and heavy tanks. However, the French Army policy was more sound and during the 1950s the other armies also concentrated on a single type of battle tank.

The design of the new tank was strongly influenced by the characteristics of the two outstanding German tanks of the latter part of the Second World War, namely the Panther and the Tiger. In fact, its aim was to produce a tank which would be as mobile as the Panther and at least as well armed as the Tiger. The outcome was the AMX-50, which was armed successively with guns of 90, 100 and finally, 120mm but which also came to weigh 59 tons.

Very sensibly, the design of the AMX-50 followed German tanks in using a 1000hp engine which was being developed for them at the end of the war, a transmission similar to that of the Panther and an overlapping arrangement of the road wheels sprung by torsion bars that was characteristic of the German tanks. However, the AMX-50 also incorporated some highly original features. In particular, it had an oscillating turret which had not been used before in any battle tank and which consisted of an upper part mounted on trunnions in the lower part. The gun was fixed in the upper part and was elevated or depressed with it, which simplified the sights and the installation of an automatic loading mechanism in the turret bustle, since there was no relative motion between them and the gun mounting.

The first prototype of the AMX-50 was built in 1949 and when it was armed with a 120mm gun in 1952 it became comparable to the US M103 and the British Conqueror heavy tanks. The AMX-50 was, therefore, as powerful as any tank of its period but it was never put into production, mainly for financial reasons. An additional reason for it not advancing beyond prototypes was a waning of enthusiasm for heavy tanks, which not only affected the AMX-50 but which also re-

Fig. 2.5 French AMX-13 light tank. (French Army)

stricted the production of the US M103 and of the British Conqueror to relatively small numbers. Moreover, the French Army's need to equip itself with tanks more effective than its ageing, US-built M4 medium tanks was met to a large extent by the delivery of several hundred M47 medium tanks under the US Military Aid Programme.

Concurrently with the AMX-50 the French Army developed another and very different tank. the AMX-13, which proved much more successful. The AMX-13 was conceived in 1946 as an air-transportable light tank. The idea of flying tanks about was unrealistic, although it was technically practicable and in spite of the fact that it was also pursued in the United States and later in Britain, where the design in the 1960s of the Scorpion light tank was stongly influenced by it. In fact, the idea of flying the AMX-13 about had to be abandoned because the Cormoran transport aircraft in which it was supposed to be carried was never put into service.

In consequence, the AMX-13 was developed not as an air-transportable light tank but as a light-weight tank destroyer. As such it had considerable merit and it represented more than one notable technical achievement. In particular, it was armed with a 75mm gun comparable to that mounted in the German Panther medium tank and yet it only weighed 14.5 tons. It was also the first tank ever to enter service with a semi-automatic loading system, which made it possible to reduce its crew to three men.

The semi-automatic loading system of the AMX-13 incorporated two six-round drums in the turret bustle, one or the other of which only had to be turned manually, by means of a quil-shaft drive, by the gunner for a round to be loaded into the gun. After firing the spent cartridge case was also ejected automatically through a trap door in the rear of the turret. The loading and the ejection systems were admirably simple, due largely to the fact that the gun and the ammunition drums were fixed relative to each other in the upper half of the oscillating turret, which was a major feature of the AMX-13. In principle the oscillating turret of the AMX-13 was not different from those of the AMX-50 but it was much more appropriate in its case because its lighter armour resulted in a small weight penalty, which is inevitably associated with the overlapping of the two parts of any oscillating turret.

The first prototype of AMX-13 was completed in 1950 and the second was sent in the same year to the United States, where its trials were followed by the design of several medium and heavy tanks with oscillating turrets. In 1950 the AMX-13 was successfully used in action by French units during the Anglo-French landing at Suez and simultaneously by Israeli forces in the Sinai. In addition to Israel, AMX-13 was acquired by several other countries, including Switzerland and India; production of its original version came to 2367 tanks (2.22). During the mid-1950s a second version was developed with a 105mm instead of the 75mm gun. It was not adopted by the French Army but about 400 were produced for the Netherlands, Argentina and Ecuador.

Apart from the AMX-50 and AMX-13, the French Army promoted the development of a series of very light vehicles to explore the possibility of using them for infantry support and for fighting enemy tanks. At first the armament envisaged for them consisted of six 105mm or four 150mm recoilless guns but in 1955 the multiple recoilless gun installations were abandoned in favour of single 90mm low-pressure guns. The best known of these vehicles, which carried the generic name *Engins Légers de Combat*, or ELC, was the ELC Even, a vehicle of 7.4 tons with a crew of two men and armed with an automatically-loaded 90mm low

pressure gun, or two 30mm automatic cannons. A batch of ten was built in 1961 but development of the ELC ceased after that (2.23).

Similar ideas were pursued in the United States and Japan, where vehicles conceptually similar to the early ELC were put into service. The US vehicle was the 8.6 ton turretless M50 Ontos, with six 106mm recoilless guns. Originally developed for the US Army, it was adopted only by the US Marine Corps, which made some use of it during the war in Vietnam (2.24). The Japanese vehicle was the Type 60 self-propelled twin 106mm recoilless gun, which was first built in prototype form in 1955 and was then produced at a low rate until 1979.

When the AMX-50 was abandoned in the mid-1950s the French Army turned its attention to the development of a much lighter battle tank, the AMX-30. This stemmed from a requirement arrived at by the French General Staff in collaboration with the German and Italian Army Staffs which called for a well-armed but lighter and more mobile type of battle tank than those developed since the Second World War in France, Britain and the United States. In fact, the new 'European tank' was to weigh only 30 tons. This meant that it could not be heavily armoured but this was not considered to be a disadvantage because of the contemporary development of anti-tank guided missiles and other weapons with shaped charge warheads which could perforate the thickest steel armour.

In 1958 France and Germany proceeded to design and then to construct alternative prototypes from which a single tank was to be chosen, although in the event each country decided in 1963 to adopt its own design. The first two prototypes of the AMX-30 were actually completed in 1960 and in 1966 production versions began to be delivered to the French Army, which eventually came to possess 1355 of them. About 680 AMX-30 were also produced for export, primarily for Saudi Arabia and Greece, and 299 have also been built, under licence, in Spain.

At 36 tons combat loaded, the AMX-30 was as light as any tank of its generation

Fig. 2.6 French AMX-30 battle tank. (French Army)

and it was also very compact, with a low height to the turret roof matched only by the Soviet T-54. Unlike the AMX-50 and AMX-13, the AMX-30 has a conventional, one-piece turret but its main armament consists of an unconventional 105mm gun with rifling having a smaller than usual angle of twist to suit its peculiar shaped charge projectiles. These, the Obus G, consist of a shaped charge mounted in ball bearings within the body of the projectile in order to minimise its rotation, and therefore the degradation of its armour-piercing performance, while retaining the accuracy advantages of spin stabilisation provided by the rotation of the outer body of the projectile.

When it was introduced, Obus G was capable, in theory, of perforating the armour of any contemporary tank. But with the advent of the new types of armour much more effective against shaped charges than conventional steel armour reliance on the Obus G became questionable. At the same time the 105mm gun of the AMX-30 could not fire APDS projectiles, which had been the best alternative, because its rifling did not impart sufficient spin to them. However, the gun proved well suited to APFSDS projectiles and their adoption in 1981 maintained its effectiveness.

During the 1960s an experimental version of the AMX-30 was fitted with a 142mm gun/ACRA missile launcher, which in many ways resembled the 152mm gun/Shillelagh missile launcher being mounted at the time in US tanks. However, like the latter, the 142mm gun/ACRA missile launcher was abandoned around 1972 and the French Army switched its efforts to the development of 120mm smooth-bore guns, which were mounted during the early 1980s in export versions of the AMX-30 – the AMX-32 and the AMX-40.

By 1985 the French Army adopted a 120mm smooth bore gun interoperable, so far as the ammunition was concerned, with the 120mm Rheinmetall gun mounted in the German Leopard 2 battle tank. A similar gun was mounted in the new AMX Leclerc battle tank which appeared in test bed form in 1987. One of the main features of AMX Leclerc is an automatic loading system which feeds the gun from a magazine in the turret bustle. The auto-loading system eliminates the need for a human loader, so that the crew of AMX Leclerc consists of three men only. Another feature of AMX Leclerc is that much more importance has been accorded in its design to armour protection than was the case with AMX-30. As a result it is far less vulnerable but also considerably heavier, weighing 53 tons combat loaded.

2.5 United States Tanks

At the end of the Second World War the US Army had three relatively recently developed types of tanks: the M24 light tank, an improved, 76mm gun version of the M4 medium tank and the M26 Pershing heavy tank. A review carried out at the end of 1945 accepted that there should continue to be three types of tanks and recommended the development of new light, medium and heavy tanks. However, funds available for the development were limited and only the new T37 light tank began to be designed in 1946. This revealed an incredible sense of priorities, since the light tank was by far the least important of the three types and its development was not going to do anything to improve the capabilities of the US armoured units.

Otherwise, the US Army devoted what resources it had to the development of new engines, transmissions and other components which was started during the war. This followed the example of an earlier policy of component development

which proved to be a very good investment during the war when it saved US tanks from the reliability problems that afflicted, for instance, contemporary British tanks. But the development of components did not eliminate the need for work on tanks as a whole.

As it was, it was only in 1949 that work began on a new, T42 medium tank. This was, in essence, a scaled-up version of what had become by then the T41 light tank but armed with a 90mm instead of a 76mm gun. Although its weight turned out to be 33.8 tons, the T42 had the same 500hp engine and the same transmission as the 23 ton T41 light tank. The first prototype of it was ready by the end of 1950 but by then the war in Korea had started and the US Army rejected it in favour of a hybrid design. This consisted of the turret of the T42 and the chassis of the existing M46 medium tanks. The latter were M26 Pershings which had been retrofitted since 1948 with the newly developed engines, transmissions and other components. The use of the M46 tank chassis ensured that the hybrid, M47 medium tank would not be underpowered as the T42 was considered to be and it provided a chassis which was already proven. The M47 tank could also be put more quickly into production in response to the US Army's urgent need for new tanks, although it involved an unnecessary continuation of a five-man crew.

Production of the M47 medium tank started in mid-1951 and continued until the end of 1953 by which time a total of 8576 was built (2.25). As they became available in 1952, M47 tanks were rushed to US armoured units in Europe and they remained the principal US battle tanks until the mid-1950s, when they began to be replaced by M48 medium tanks. As this happened, the M47 tanks were passed on to Allied armies and in particular to the German, French, Belgian and Italian armies as well as Spanish, Turkish and several others. The M47 suffered from having been rushed into production and its stereoscopic rangefinder was difficult to use. Its operating range was also short but it proved to be a durable tank and its effective life could have been longer still if it had been rearmed with a

Fig. 2.7 US M47 medium tank.

105mm gun and retrofitted with a diesel engine.

The M48 tank which replaced it was no better so far as its main armament was concerned, as it was armed with the same 90mm gun, and its automotive characteristics were much the same, as was its weight of 44.9 tons. However, the M48 had an ellipsoidal cast hull based on that of the T43 heavy tank and a semi-ellipsoidal cast turret, the shape of which, together with their thicker armour, offered greater ballistic protection. The use of an ellipsoidal hull also involved the elimination of the hull machine-gunner, which brought the M48 in line with the general trend towards four-man crews.

Compared with the M47 the M48 had the advantage of a lower silhouette but this was quickly spoilt by the peculiar addiction of the US Army to the mounting of 12.7mm heavy machine guns with which tank commanders might engage some targets on their own, even though this diverted them from their proper role of commanding the tanks. In the case of the M48 this addiction resulted in the installation on the M48A1 and the following models of a large commander's machine gun cupola. This not only increased the overall height of the tank but also made the commander more vulnerable by raising his head above the level of the turret armour and left much to be desired from the point of view of vision from within the tank.

Design of the M48 started in 1950 and production of it began in 1952. It continued until 1959, when it was succeeded by the M60 battle tank and when the number produced reached a total of 11703 tanks (2.26). After the M48 displaced the M47 as the main battle tank of the US Army it was also supplied to other armies and in particular to the German Army, which subsequently passed some of its M48 tanks on to Israel.

Concurrently with the development of the M47 medium tank, the US Army also developed the T43 heavy tank, a 56.7 ton vehicle armed with a 120mm gun. Its design was based on the experience gained with four different experimental heavy tanks designed during the Second World War but only completed in 1946 and

Fig. 2.8 T48 prototype of the US M48 medium tank.

1947. These included the 65.5 ton T30 which was armed with a 155mm gun and the very similar T34, which was armed with a 120mm gun. Design of the T43 began in 1948 and with the outbreak of the Korean War it was rushed into production as the M103 heavy tank, with the result that the first was completed in 1952. However, its production was terminated at the end of 1954, when only 300 had been built.

At least two more heavy tanks were designed after 1951, the T57 and T77, both of which were to be armed with 120mm guns mounted in oscillating turrets. But their development was terminated in 1958 without either being completed. Thereafter development effort was concentrated on medium or main battle tanks.

An early attempt to advance on the M48 medium tank amounted to proposals made in 1953 to develop a lighter and more economical medium tank from the basis of the T42, which was rejected three years earlier. The proposed T87 tank was also rejected in 1954. But an experimental T69 tank consisting of an oscillating turret with a 90mm gun and an automatic loading system mounted on a T42 chassis was completed in 1955 and continued to be tested until 1957.

A more promising attempt to improve on the M48 consisted of the development for it of three different new turrets mounting a 105mm gun, work on which began in 1952. Two of the turrets were conventional but the third was again of the oscillating type and contained an automatic loading system, as did one of the conventional turrets. The installation of these turrets on M48 chassis resulted in the T54 series of experimental tanks but, although there was much sense in the most conventional of them, the T54E2, they were all abandoned in 1957 in favour of an entirely new and lighter tank, the T95 (2.27).

Development of the T95 began in 1955 and involved several new components and design features which had not been used before in US tanks. These included a 90mm smooth-bore gun firing APFSDS projectiles, a novel OPTAC fire control system incorporating a light-beam rangefinder and a new transmission (2.28). Some of the features of the T95 were promising but others, like the rigid mounting of the gun without a recoil system, which had been tried in some German vehicles during the Second World War, were highly questionable. They also jeopardised unnecessarily the development of the good features of the T95 and of the tank as a whole. In fact development of the T95 ran into serious difficulties and was stopped in 1959.

As there was no other immediate solution to the problem of modernising its tank fleet, the US Army decided in 1958 to go back to the M48A2 and to produce in effect, a new version of it with a more powerful gun and a diesel engine. After comparative tests with five other US guns, it was decided to adopt a slightly modified version of the 105mm L7 gun which had been developed in Britain for the Centurion. The installation of this gun and the AVDS 1790 diesel together with a number of modifications transformed the M48A2 into the M60, which was adopted in 1959 as an interim main battle tank. But once its production started in 1960, the M60 went on being produced for a quarter of a century. What is more, in 1962 and again in 1978 and 1979 its annual rate of production exceeded 1000 tanks and in 1980 the total number produced reached 11634, excluding engineer and bridging versions (2.29). Some more were produced later, the last being completed in 1987.

In the meantime a review of tank development carried out in 1957 led the US Army to the conclusion that a new battle tank should be armed not with a high velocity gun but with a guided missile system. An agreement for the joint development of such a tank with Germany was signed in 1963 but its design did not start

in earnest until 1965. However, prior to this a gun-Shillelagh missile launcher began to be developed for the Armoured Reconnaissance/Airborne Assault Vehicle, which was eventually adopted as the M551 Sheridan. In 1961 studies also began of the possible installation of a similar, 152mm gun-launcher in the M60 tanks. This led to the modification of 540 M60 into the M60A2, which mounted the 152mm gun-launcher in a novel type of turret. The latter had a commendably low frontal area but was spoilt even more than other contemporary US tank turrets by the addition of a large commander's machine gun cupola.

Production of the M60A2 began in 1966 but problems with the gun-launcher and other difficulties delayed its entry into service until 1974. Six US tank battalions stationed in Germany were equipped with it and it was intended to engage enemy tanks beyond the effective range of tank guns. But it proved more difficult to operate and to maintain than the standard gun-tanks and was withdrawn from service around 1982.

The M551 Sheridan, in which the 152mm gun-launcher was originally mounted, began to be developed in 1959 and after the usual testing of prototypes was put into production in 1966. It was conceived as a successor to what was originally the T41 and then the M41 light tank. About 5500 of the M41 were built during the early 1950s, in spite of the fact that it was far too big for a reconnaissance vehicle, too heavy for use by the airborne forces and insufficiently armed to fight battle tanks. As it weighed 15.8 tons, the Sheridan had the merit of being lighter and its 152mm gun-launcher made it capable of destroying enemy tanks. But it was still too big for reconnaissance, too heavy to be an efficient air-transportable anti-tank vehicle and, like all light tanks, too lightly armoured to be an assault vehicle. Its vulnerability as a fighting vehicle was demonstrated when it

Fig. 2.9 US M60E1 battle tank.

was used in Vietnam in 1969 and its capabilites as an air-transportable anti-tank vehicle, which was the one thing that might have justified its development, were never put to test. As it was, almost all of the 1700 M551 Sheridans which had been built were withdrawn from service in 1979.

The MBT-70 tank on whose joint development the United States and Germany embarked in 1963 was armed with a 152mm gun-launcher with a longer barrel than the gun-launchers of the M60A2 and the M551 Sheridan. In consequence it could fire APFSDS projectiles as well as shaped charge and high explosive projectiles and Shillelagh guided missiles. Moreover, the gun-launcher was provided with an automatic loading system located in the turret bustle and in addition to the missile guidance system there was also an integrated fire control system with a laser rangefinder and a ballistic computer. The automatic loading system was considered essential for firing on the move and made it possible to reduce the crew of the MBT-70 to three men.

The three crewmen were all located in the turret, which meant that they could be within an environmental control capsule created within the turret. This protected them against radioactive dust and airborne chemical and bacteriological agents, and also provided heating and air conditioning. The location of the whole crew in the turret had been considered in the United States since the mid-1950s, or even earlier (2.30). Its initial objective was to lower the silhouette of tanks by eliminating the traditional two-tier arrangement which put the main armament above the driver. However, the location of the driver in the turret made it necessary to provide him with a counter-rotating capsule, so that he would face forward no matter which way the turret was turned. This inevitably complicated driving controls and driving itself, as well as using up a considerable amount of space within the turret.

The MBT-70 was also intended to be exceptionally agile and, therefore, to have a power-to-weight ratio of not less than 30hp per ton, which was higher than that of any tank of comparable weight built until then. As its weight was planned to be 45.3 tons, this implied the use of an engine of as much as 1500hp, which was considerably more than the output of any earlier tank engine. To increase its speed off-roads the MBT-70 was also provided with an adjustable hydropneumatic suspension.

Some features of MBT-70 were highly commendable and were subsequently also incorporated in other tanks. But others were questionable. They included the location of all the crew in the turret, a retractable, remotely-controlled cupola mounting the secondary armament consisting of a 20mm cannon, and a variable compression ratio engine. But whatever the merits or demerits of the individual features, they were for the most part untried and incorporating them all in the MBT-70 meant that its development was going to be, at best, difficult and costly. The number and character of the features incorporated in the design of the MBT-70 also meant that it was going to be complex and costly to produce.

The first US and German prototypes of MBT-70 were actually built to schedule in 1967. But the cost of its development was becoming much higher than had been optimistically expected and by the end of 1969 the German Government decided to pull out of it. The US Army persevered with what was supposed to be an austere version, which was designated XM803. But in spite of claims that it would be considerably less expensive, the production cost of the XM803 was estimated in 1971 to be three to four times that of the M60A1. This was too much for the US Congress, which questioned the need for a tank "as complex, as sophisticated, and as costly as the austere MBT-70/XM803" and decided in 1971 to withhold funds

for its further development (2.31).

As a result, the MBT-70/XM803 programme was terminated at the end of 1971 and in the following year the US Army embarked on the development of yet another tank, originally designated XM815. The new tank, which became the XM-1, was to be simpler and less costly than the MBT-70/XM803 and it was to be developed relatively quickly in view of the US Army's increasingly urgent need for a new battle tank. Moreover, the highest priority was no longer to be accorded in its design to fire-power, as it was in the case of MBT-70, but to crew survivability.

All this led to a tank with a conventional configuration and a four man crew but with much better protection than earlier US tanks. The latter was particularly effective against shaped charge weapons, thanks to the adoption of the Chobham armour which had been developed in Britain. To help increase its survivability, it was also significantly lower and it had no commander's machine gun cupola to ruin its silhouette.

To reduce development costs, its components were chosen to a large extent from those already in existence and in particular from those developed as part of the MBT-70 programme. The latter included two alternative engines, both of which developed 1500hp. This made the XM-1 very agile even though it was somewhat heavier, at 52.6 tons, than the MBT-70.

The XM-1 was no longer required to fire guided missiles and in view of this and the problems encountered with the 152mm gun-launcher of the MBT-70 the only course that was open was to go back to the 105mm gun which had been used already for 13 years in the M60 tanks. This retrograde step was made inevitable by the rash decisions taken by the US Army in 1957 to concentrate on guided missile

Fig. 2.10 US-German MBT-70 tank. (US Army)

launchers, which caused it to abandon the development of new tank guns. To be fair. the adoption of the 13-year old 105mm gun was alleviated by the contemporary development of APFSDS ammunition which made it more effective than it had been before. Some consideration was also given to retrofitting at a later stage a 110mm gun which was being developed in Britain. However, the latter proved no better than the 105mm gun with its new APFSDS ammunition during trilateral gun trials carried out in Britain in 1975. This was due to the fact that the 110mm gun was still only provided with APDS ammunition, to which its British developers remained wedded, in spite of the evidence that APFSDS ammunition was becoming superior to it, because of the success they had with it until then.

The actual development of the XM-1 was carried out on a competitive basis, contracts for it being awarded in 1973 to Chrysler and to General Motors. Both companies completed their prototypes in 1975 and after trials the Chrysler XM-1 was chosen in 1976 for further development on the grounds that it was being offered at a lower cost. The principal engineering difference between the two was that the General Motors prototype was powered by a variable compression ratio diesel. which was not entirely successful, while the Chrysler prototype was powered by a gas turbine, which was expensive to produce and which, in spite of repeated claims to the contrary, proved to have a high fuel consumption. A conventional diesel would have been a better choice for either of the two designs and one of 1500hp had been developed in Germany for the MBT-70 but it was not considered for the XM-1.

Whichever of the two US prototypes won, it was intended that it should be evaluated in competition with the German Leopard 2 with the view of achieving standardisation between the US and German tank fleets, ostensibly even to the

Fig. 2.11 US M1A1 tank. (General Dynamics Land Systems)

extent of adopting the same tank for both. In the event all that happened was that the US Army decided in 1978 to adopt the 120mm smooth-bore gun produced in Germany for the Leopard 2. The decision was taken after trials carried out in 1977 when the German 120mm smooth-bore gun was compared with the US 105mm tank gun, which by then was 18 years old, and a new 120mm rifled gun hastily developed in Britain to suit US requirements.

Having won the competition, Chrysler produced the first of a pre-production batch of eleven XM-1 tanks in 1978 and in 1980 began to build M1 tanks, still armed with 105mm guns. It was originally intended to produce a total of 3312 M1 tanks but by 1985 their number was increased to 7467. Of this total 4199 were to be M1A1 tanks armed with 120mm guns, the first production model of which was completed in 1985. By then the responsibility for the M1 had passed to the Land Systems Division of General Dynamics, who had taken over its development and production from Chrysler in 1982.

2.6 German Tanks

Development of tanks in Germany came to a halt in 1945 and was only resumed after the agreement reached with France in 1957 for the joint design, development and production of a standard European tank. Studies carried out in Germany prior to this led to a requirement for a relatively light but very agile tank of 30 tons with a power-to-weight ratio of 30hp per ton, and armed with a 105mm gun. The development of such a tank was entrusted to two industrial groups, each of which produced two prototypes in 1960. Even before these were completed work started on a second series of prototypes, which were armed with the British 105mm L7 gun instead of the 105mm Rheinmetall gun mounted in the first four prototypes. Twenty six of the redesigned prototypes were ordered from the industrial group headed by the Porsche company and they became the basis of the Leopard tank which was adopted for production for the German Army in 1963. The first production tank was delivered in 1965 and production for the German Army continued until 1976, by which time 2437 Leopard gun-tanks had been produced for it. A further 1404 Leopard gun-tanks were produced between 1968 and 1979 for Belgium, Denmark, Italy, Netherlands, Norway, Australia and Canada. Another 720 were built under licence in Italy between 1974 and 1989 and in 1981 production was resumed in Germany to fulfil orders from Greece for 106 and from Turkey for 77 gun-tanks (2.32).

As with other tanks, the weight of the Leopard rose from 34.8 tons of the first prototype to 42.4 tons of the final, Leopard 1A4 version. The latter has a power-to-weight ratio of 19.6hp per ton, well below the 30hp per ton originally envisaged. Nevertheless, the Leopards are highly agile and have acquired an enviable reputation for automotive performance and reliability, while the progressive increases in weight have brought about improvements in their armour protection.

Soon after the first pre-production Leopards were delivered in 1963, German and US Governments agreed to develop jointly a new tank which became the MBT-70. Two years later agreement was reached about its military characteristics which resolved, among others, the difference between the contemporary US policy of using guided missile launchers as the main armament of tanks and the German preference for high velocity guns (2.33). This was achieved by the adoption of a 152mm gun-launcher with a long barrel which enabled it to fire APFSDS projectiles with a high muzzle velocity, as well as shaped charge projectiles and Shillelagh missiles. In contrast, the earlier, short-barrelled US 152mmm gun-launchers

Fig. 2.12 German Leopard 1 tank.

Fig. 2.13 German Leopard 2 tank. (Krauss-Maffei)

mounted in the M551 Sheridan and the M60A2 could not fire high velocity kinetic energy projectiles.

However, as already mentioned in connection with the development of US

tanks, the German Government decided in 1969 to withdraw from the MBT-70 programme and its outcome in Germany became limited to the construction of six prototypes, which was the same as the number of prototypes built in the United States.

In the meantime, work was started in Germany in 1967 on a new and more conventional tank of 40 tons armed with a 105mm gun (2.34). This led to the construction of two 'experimental development' prototypes, which began to be tested in 1970. Even earlier, in 1965, Rheinmetall started to develop smooth-bore tank guns of 105 and 120mm (2.35). This was in marked contrast to what was happening in the United States where, after the difficulties experienced with the 90mm T208 and 105mm T210 smooth-bore guns mounted in the T95 tank, a new and very promising 120mm smooth-bore Delta gun was developed during the early 1960s only to be abandoned in 1965.

After withdrawing from the MBT-70 programme, the German Government decided in 1970 to develop a new battle tank based on the 'experimental developments', the Rheinmetall smooth-bore guns and the 1500hp power pack developed for MBT-70. The new tank was called Leopard 2: 16 prototypes were ordered, 10 armed with the 105mm and 6 with the 120mm smooth-bore guns. The prototypes were completed between 1972 and 1974. By then the US authorities had undertaken to test the Leopard 2 as part of the XM-1 tank programme and to suit US requirements a new, Leopard 2 AV version was produced in the form of two prototypes. The most important feature of the new version was that it incorporated a German equivalent of Chobham armour, which brought its weight up to 54.5 tons.

In consequence, one of the two Leopard 2 AV prototypes which was temporarily fitted with the standard 105mm L7 rifled gun to make it comparable in this respect with the US XM-1 was flown in 1976 to the United States in a C-5A Galaxy for trials. Compared with the Chrysler XM-1, the Leopard 2 AV was adjudged to be "about equal in mobility and firepower, but the XM-1's armour protection was judged markedly better", although it was noted that the difference may have been due to the haste with which the Leopard 2 was redesigned to suit US requirements (2.36). Nothing more happened so far as the United States was concerned except for the adoption of the 120mm smooth-bore gun which the Leopard 2 AV was designed to have. In Germany on the other hand Leopard 2 AV became the model for the 1800 tanks which were ordered for the German Army in 1977. The first of them came off the production line in 1979. In the same year the Netherlands placed an order for 445 Leopard 2 and in 1983 the Swiss Army also decided to acquire 380 Leopard 2, most of which were to be built under licence in Switzerland.

Like its predecessor, Leopard 2 has a conventional configuration and a four man crew. However, even before it was put into production alternative configuration began to be considered. One which came to be favoured during the early 1980s involved the installation on the Leopard 2 chassis of a new, reduced-height, two-man turret with an auto-loader in the bustle. But this was not considered to offer any immediate advantage, overall, over the standard version.

Much more radical alternatives emerged out of investigations, begun during the 1960s, into the possibility of tanks using violent evasive manoeuvres to avoid being hit by anti-tank guided missiles. In the first instance this led to the RVT-2 experimental vehicle based on the chassis of the US M41 light tank powered by an 1800hp engine. This resulted in a vehicle with a power-to-weight ratio of 70hp per ton, which made it very agile. The RVT-2 was followed by the construction of the

VT 1-1 turretless vehicle with two 105mmm L7 guns in semi-fixed mountings. The VT 1-1 was built between 1972 and 1974 and was based on one of the MBT-70 chassis but with the engine uprated to 2000hp, which gave it a power-to-weight ratio of more than 50hp per ton (2.37). In consequence, it combined a high degree of agility with a high probabilty of hitting targets if it fired salvoes from its two guns. The VT 1-1 was followed by VT 1-2, which was similar but which was armed with two 120mm smooth-bore guns and powered by an engine uprated to 2200hp. However, in 1976 the development of the turretless tanks with two guns in semi-fixed mountings was discontinued.

More recent investigations in Germany into possible departures from the conventional configuration of tanks have involved studies of vehicles with guns mounted externally on pedestals and of turreted tanks with two-man crews located in the turret.

2.7 Swedish, Swiss and Israeli Tanks

During the decade preceding the Second World War the Swedish Landsverk company produced with the help of some German engineers a number of designs which were in the forefront of tank development. But as Sweden remained neutral during the war its tank development fell well behind that in the belligerent countries and no serious attempt was made to revive it until the mid-1950s. Landsverk then embarked on the development of a very avanced, 45 ton KRV battle tank which was to have a Bofors-designed turret with an automatically loaded 150mm smooth-bore gun.

However, development of the KRV tank did not proceed beyond the construction of two chassis in 1957, because the Swedish Army abandoned it in favour of another and even more unconventional tank, the turretless S-tank. Development of the S-tank was initiated in 1956 by S E Berge of the Swedish Army Materiel Department, and led in 1959 to the award of a contract to Bofors for the construction of two prototypes. These were followed by a pre-production series of ten tanks and in 1964 the Swedish Army placed a production order with Bofors (2.38). The first production tank was delivered in 1967 and the last in 1971, by which

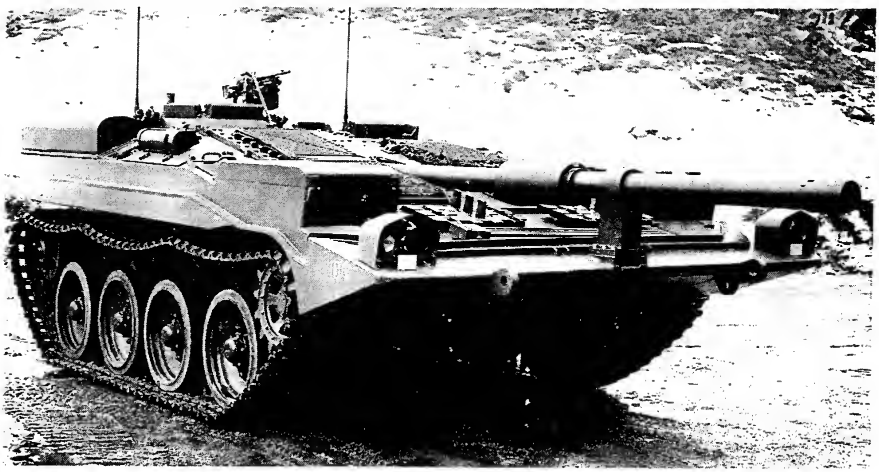


Fig. 2.14 Swedish S-tank, or Strv 103. (Bofors)

time a total of about 300 had been built.

The S-tank, or Strv 103 according to its Swedish Army designation, differs from all previous tanks in having the mounting of its gun fixed in the hull. In consequence, its 105mm gun can only be aimed in azimuth by turning the whole vehicle and in elevation by altering the pitch of the hull by means of an adjustable hydropneumatic suspension. On the other hand, the adoption of a fixed gun mounting eliminated the need for the space otherwise required within a tank for the movement of the breech end of the gun and made it possible to install a relatively simple automatic loading system because of the absence of relative angular movement between the breech of the gun and the ammunition magazine. A similar situation existed already in tanks with oscillating turrets which contained the ammunition magazine in the bustle. Nevertheless, the S-tank was the first tank to enter service with a fully automatic loading system.

The provision of an automatic loading system eliminated the need for a human loader while the adoption of a fixed gun mounting made it possible to provide the S-tank with integrated gun and driving controls. As a result, it can be operated, in full, by one man, which can not be done in any other tank. The normal crew of the S-tank consists of three men: commander and driver/gunner, who sit on either side of the gun and who are provided with duplicate driving and gun controls, and a radio operator who sits facing to the rear and who can drive the tank in reverse.

The S-tank also has a unique engine installation consisting of a diesel for normal running and of a gas turbine which is switched on when additional power is required. The two engines are located at the front of the hull and for the first time in any tank they have been considered to form part of the protection of the crew against attack from the front.

The one major disadvantage of the S-tank, which is inherent to turretless tanks with fixed gun mountings, is that it can not engage targets on the move, unless they happen to be straight ahead of it, and this has been considered to outweigh all its other advantages. In spite of this, further developments of the S-tank concept were considered in Sweden during the 1970s. However, by the end of 1974 the Swedish Army came to favour another design concept, called UDES-19. This involved an external location of the gun on a pedestal above a one-man turret and the loading of the gun from an amunition magazine at the rear of the hull by means of an arm rotating about the turret. But this promising concept did not advance beyond test rigs and a mock up, because the Swedish Army switched its attention once again, this time to the development of a tank destroyer.

The outcome of this was the construction of an experimental articulated vehicle called UDES-XX-20. This represented a revival of interest in articulated armoured vehicles, which had manifested itself around 1960 in the United States, but like UDES-19 UDES-XX-20 incorporated the novelty of a pedestal-mounted gun. The gun was to have been remotely controlled and fed by a rotating arm, which would have had to transfer rounds from one half of the vehicle into the other. The whole arrangement was complicated and UDES-XX-20 would have required a good deal of effort and money to develop. It is not surprising therefore that the Swedish Army decided to abandon it in 1983, in spite of the exceptionally low ground pressure and the outstanding obstacle crossing capabilities which it offered.

In contrast to Sweden, no tanks were built in Switzerland until the late 1950s. The construction of the first Swiss tank followed studies begun in 1951 by the Technical Section of the Swiss General Staff of the possibility of designing and

producing a tank in Switzerland. The outcome of these studies was positive and the task of developing a tank was entrusted to the Federal Construction Works in Thun, the principal Swiss ordnance establishment, which completed the first two prototypes in 1958. They were followed by a pre-production series of ten tanks, called Pz.58, which were built by 1961 and which were armed with a modified version of a Swiss 90mm anti-aircraft gun. However, by then the 105mm L7 tank gun had appeared in Britain and the Swiss Army decided not to produce the Pz.58 but a version of it armed with the British gun, which was designated Pz.61 (2.39).

A production order for 150 Pz.61s was placed in 1961 and the first was completed in 1964. Very sensibly for a first attempt at tank design, the Swiss Army adopted a conventional configuration for the Pz.61. However, its design incorporated a number of novel or unique features, which included an independent suspension sprung by means of stacks of conical discs, or Belleville washers, and a double-differential steering system with a hydrostatic steering drive. The Pz.61 was only the second tank ever to be produced with such a steering system – the first being the French Char B – and was ahead of its general adoption during the 1970s.

After the last of the Pz.61 was completed the Swiss Army decided to acquire more tanks of its type but in an improved form, which was designated Pz.68 and which weighed 39.7 tons, compared with 38 tons of the Pz.61. The first of the Pz.68 was built in 1971 and the last in 1984, by which time a total of 390 had been produced.

During the 1970s the Swiss Army began to study a possible successor to the Pz.61 and Pz.68 and by 1979 Contraves produced an advanced design of a 50 ton tank which was designated NKPz. This was to be a front-engined vehicle with a crew of three and a turret-mounted 120mm smooth-bore gun fed automatically from a magazine at the rear of the hull. In several respects the NKPz was

Fig. 2.15 Swiss Pz.68 tank.

comparable to the German Leopard 2 but it would have been an advance on it by having an automatic loading system, an ammunition magazine separated from the crew and a hydropneumatic suspension. However, the Swiss military authorities decided not to develop the NKPz, mainly because Switzerland was considered to lack the infrastructure necessary for the development of such a sophisticated tank. Instead, the Swiss Government decided to produce the Leopard 2 under licence, as already mentioned.

Unlike Switzerland, Israel started to develop a battle tank not from choice but because of its inability to obtain new battle tanks from other countries. Thus, until 1972, when they received some new M60A1 tanks from the United States, Israel Defence Forces had to make do with second-hand tanks, albeit modernised in most cases. In 1966 negotiations began with Britain about the procurement of the then new Chieftain tanks and two were actually sent to Israel for trials. But in 1969, under pressure from Arab countries, the British Government went back on its offer. This led the Israeli Government to reconsider the situation and to decide in 1970 to develop an indigenous battle tank.

The tank was called Merkava and its development was very successfully directed by Major General I Tal. Thus, in spite of the fact that Israel had not built any tanks before, the Merkava was designed and two prototypes of it were completed by the end of 1974. Production followed and in 1979 the first Merkavas were delivered to the Israeli Armoured Corps. In 1982 Merkavas were successfully used during the fighting in Lebanon and by the end of 1983 an improved, Mark 2 version began to be delivered to Israeli armoured units (2.40).

The Merkava is unconventional in having its engine compartment at the front of the hull where it has been located to make the power pack contribute to the protection of the crew against the most likely direction of attack. The same approach has been adopted all round the Merkava, making the suspension and other components contribute to its protection. This, together with spaced layers of

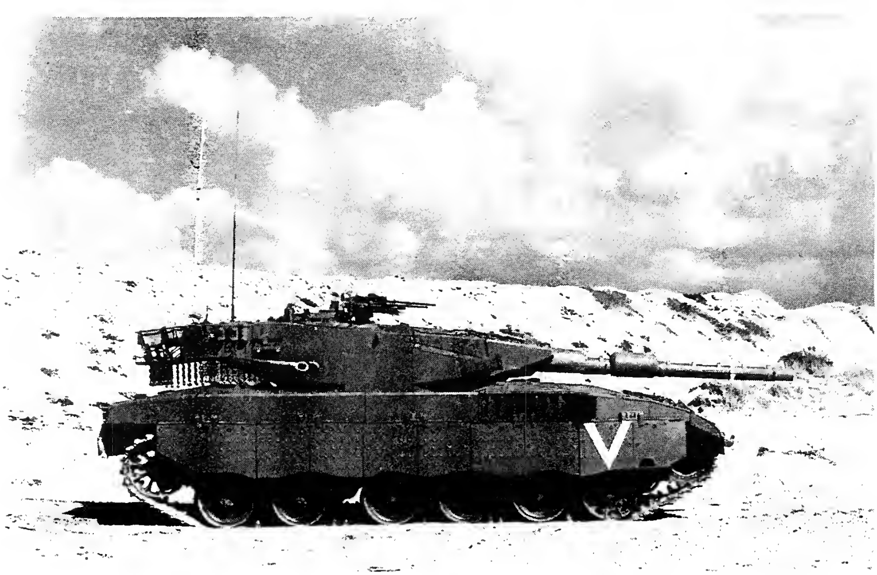


Fig. 2.16 Israeli Merkava Mark 3. (IDF)

armour, provided its crew and ammunition – which are the two most vulnerable elements in any tank – with a high degree of protection, even before special armour was added on the Merkava Mark 2. In addition, the turret of the Merkava has an unusually small frontal area, which reduces the chances of it being hit, particularly in defensive, hull-down positions.

The location of the engine at the front of the Merkava made it possible to locate most of the ammunition at the rear of the hull, where it is least vulnerable to direct fire. The ammunition is stowed in fire-proof containers and there is a passage between them leading from the fightng compartment to a hatch in the rear of the hull, which provides the crew with an alternative and often safer as well as more comfortable way of entering or leaving the tank than through the top hatches. The ammunition containers are removable and this, together with the rear hatch, makes it possible to use the ammunition stowage space for other purposes, such as carrying a command team, six or more infantrymen and four stretcher cases. However, this can only be done at the expense of most of the ammunition load. Under normal circumstances the rear of the hull is filled with ammunition containers and the Merkava does not carry any men other than its crew of four.

Production of Merkava Mark 2 as been followed by development of the Mark 3 version, which represents a considerable further advance. In particular, it is armed with a 120mm smooth-bore gun instead of the 105mm rifled gun of the first two versions and has more special armour of a more advanced type. Moreover, for the first time in any tank, much of the special armour is in the form of replaceable modules. As a result, more than half of the entire protection of the Mark 3 can be changed if even more effective forms of special armour are devised (2.41).

2.8 Japanese, South Korean and Brazilian Tanks

Development of tanks in Japan was stopped in 1945, when it was occupied by US forces, but was resumed in 1954, after the creation of the Japanese Ground Self-Defence Force. Its initial outcome was the construction in 1957 of four prototypes of what was initially called the ST-A medium tank which, after being accepted in 1961, became the Type 61. The first production models of this tank were accepted in 1962 and eventually 560 were produced. But in 1984 it began to be withdrawn from service.

The Type 61 was a 35 ton tank armed with a 90mm gun. Although it was lighter and more compact, it was comparable in general terms to the US M47 medium tank. However, it incorporated at least two design features which constituted a link with the development of Japanese tanks before 1945. One of them was its 600hp V-12 air-cooled diesel, a type of engine which the Japanese Army began to develop in 1932, well ahead of others. The other and much more questionable link with the past was the use of a front sprocket drive in combination with a rear location of the engine. This had been used before 1945 not only in Japanese but also in German and US tanks, but it was subsequently abandoned because of the amount of space it wasted within the armour envelope of tanks. In consequence, Type 61 was the only battle tank to be produced with such a combination after 1945.

Soon after Type 61 came into service, the Japanese Defence Agency recognised the need for a more effective tank. As a result work was started in 1964 on a new tank, the ST-B, and two prototypes of it were completed in 1969. Adopted in 1974 as the Type 74, it began to be produced in 1975 and successive orders for it covered a total of 850 tanks up to 1988.

At 38 tons Type 74 was still relatively light but it represented a major advance

Fig. 2.17 Japanese Type 74 tank.

Fig. 2.18 South Korean Type 88 tank. (Hyundai)

on Type 61 in having a 105mm L7 gun, a much better profiled turret and an adjustable hydropneumatic suspension. It no longer had a front sprocket drive but still incorporated a link with earlier Japanese developments in the form of a unique, two-stroke, V-10, air-cooled diesel of 720hp, which was developed from a high-output diesel designed in Japan during the Second World War for motor torpedo boats (2.42, 2.43).

In 1976 the Japanese Defence Agency decided to embark on the development of a third tank, originally called the ST-C and then TK-X. The first two prototypes of

this tank were built in 1985 and it represents another major advance in the design of Japanese tanks. In particular, it is superior to Type 74 in having a Rheinmetall 120mm smooth-bore gun and much more effective protection, which incorporates multi-layered armour. The gun is automatically loaded from an ammunition magazine in the turret bustle and, as a result, the crew of the TK-X consists of only three men. Because of its much higher level of armour protection, the TK-X is considerably heavier than Type 74, weighing about 50 tons. But so far as its agility is concerned, the heavier weight is more than compensated for by the installation of a 1500hp diesel. But in one respect the design of the TK-X represents a retrograde step compared with that of Type 74, namely in having a hybrid suspension with hydropneumatic units only at the front and rear road wheel stations and with torsion bar springs for the intermediate road wheels.

Quite independently of the Japanese adoption of a hybrid suspension for the TK-X. a hybrid suspension has also been adopted for the Type 88 battle tank produced in South Korea. Type 88 stems from a decision taken in the mid-1970s by its president that South Korea should have a tank of its own. To develop what was originally called the Republic of Korea Indigenous Tank, or ROKIT, help was sought abroad and in 1978 four US companies submitted alternative designs. This led in 1981 to the selection of a design produced by Chrysler Defense, who completed the first two prototypes in 1983. Two years later Type 88 began to be produced in Korea.

In several respects Type 88 is similar to the US M1 tank, which is not very surprising since the two tanks were designed by much the same team of US engineers. In particular, it has the same general configuration and similar special

Fig. 2.19 Prototype of Engesa EE-T1 Osorio tank. (Engesa)

armour, as well as the same 105mm M68 gun, although the latter is there at the specific request of the South Korean military authorities who wanted to standardise on it. However, Type 88 differs from the US M1 not only in having a hybrid suspension but also in being powered by a diesel engine, instead of a gas turbine, and in having a superior fire control system (2.44).

The speed with which the South Korean Type 88 was developed was improved upon in Brazil where the Engesa Company started in 1982 to study the development of a battle tank in two versions, which would differ primarily in their main armament and fire control systems, and consequently in cost. Thus one version was to be armed with the widely used 105mm rifled gun and have a relatively simple fire control system while the other was to have a more powerful, 120mm smooth-bore gun and a fire control system as sophisticated as that of any tank in the world.

In either form the tank was called the EE-T1 Osorio and although Engesa had not built a tank before it completed the first prototype of the 105mm gun version in 1985. A year later Engesa completed a prototype of the 120mm gun version, which in 1987 very successfully competed in Saudi Arabia with the British Challenger and the French AMX-40 as well as with the US M1A1 (2.45).

Bearing in mind that the Osorio was the first tank ever designed in Brazil, Engesa very sensibly adopted for it a conventional configuration and secured the assistance of the British Vickers company in the design and construction of the turrets. It also used a maximum of existing components, although some of them, such as the MWM diesel, had not been used before in any tank while others, such as its hydropneumatic suspension, were new and untried. Nevertheless, the speed with which Engesa proceeded from its early studies to the successful construction of the first two prototypes was remarkable and stood in marked contrast to the time taken in most other countries to develop new tanks.

2.9 References

2.1 B H Liddell Hart, ed., *The Soviet Army*, Weidenfeld and Nicolson. London. 1956. pp.315 and 319.

2.2 W G Dolvin, 'Mobile Antitank Weapons in Armored Warfare', *Armor*. Vol.61. No.6. November-December, 1952, p.8.

2.3 'Task Force Razor', *Armor*, Vol.64, No.3 May-June, 1955, pp.4-13.

2.4 A Harrigan, 'Tanks in Nuclear War – A Russian View', *Armor*, Vol.72. No.4, July-August. 1963. p.40.

2.5 M W Ireland, 'MBT70/XM803', *Armor*, Vol.79, No.4, July-August, 1970, p.33.

2.6 M Norman. *Conqueror Heavy Tank*, AFV/Weapons Profile No.38. Profile Publications. Windsor. 1972.

2.7 'New Developments', *National Defense*, Vol.60, No.333, November-December. 1975. p.231.

2.8 'Score: TOW/Cobras 20, Armor 1', *Armed Forces Journal*. September. 1972. p.20.

2.9 I Smart. 'Time Running out for the Tank', *The Times*. 24 October. 1973.

2.10 J J McGrath. 'The Battle of El Firdan', *Armor*, Vol.92, No.3. May-June. 1983. pp.9-13.

2.11 E C Ludvigsen. 'Chrysler Awarded XM1 Development Contract'. *Army*, December 1976, p.54.

2.12 H von Manteuffel, 'The Tank Battle of Targul Frumos'. *Armor*. Vol.65. No.6, November-December, 1956. pp.48-52.

2.13 J Magnuski. *Wozy Bojowe LWP 1943-1983*, Ministry of National Defence. Warsaw. 1985. pp.141-156.

2.14 J Magnuski. op.cit., pp.109-128.

2.15 L W Williams and J E Backofen, 'Soviet Kinetic Energy Penetrators', *Armor*, Vol.87, No.6. November-December, 1978. pp.43-45.
2.16 R P Hunnicutt. *Patton*. Presidio Press. Novato, 1984, p.149.
2.17 *The Soviet Union and the NATO Powers*, Institute for Strategic Studies, London, c.1959. p.2.
2.18 B C Clarke, 'Objectives for Armor of the Future', *Armor*, Vol.68, No.4, July-August, 1959. p.34.
2.19 *Soviet Military Power 1985*, US Government Printing Office, Washington, 1985, p.66.
2.20 D Fouquet, 'The Great East-West Divide', *Jane's Defence Weekly*, Vol.11, No.6, 11 February, 1989, p.221.
2.21 C F Foss, ed., *Jane's Armour and Artillery 1981-82*, Jane's Publishing Co., London. 1981. p.75.
2.22 P Touzin, *Les Vehicules Blindés Français 1945-1977*, Editions EPA, 1978, p.30.
2.23 P Touzin, op.cit., pp.41-50.
2.24 'The Ontos', *Armor*, Vol.64. No.5. September-October, 1955, p.19.
2.25 R P Hunnicutt, op.cit., p.59.
2.26 C F Foss, op.cit., p.96.
2.27 R P Hunnicutt, ibid., pp.47-51 and 126-142.
2.28 N N Shiovitz, 'The T-95 Tank', *Armor*, Vol.85, No.1. January-February, 1976, pp.25-27.
2.29 G A Halbert, 'World Tank Production', *Armor*, Vol.90, No.2, March-April, 1981, p.44.
2.30 'Armor of the Future'. *Armor*, Vol.67. No.4, July-August, 1958, p.15.
2.31 *Department of Defense Appropriation Bill 1972*, House of Representatives, 92nd Congress. 1st Session, Report No.92-666, November, 1971, pp.73-74.
2.32 W J Spielberger, *From Half-Track to Leopard 2*. Bernard & Graefe, Munich, 1979, pp.113-130 and 168-171.
2.33 J A DeAngelis, 'Armor's Equalizer for Future Tank Warfare', *Armor*, Vol.76, No.6, November-December, 1967, p.7.
2.34 W J Spielberger, op.cit., pp.207-213.
2.35 'The 120mm Smooth Bore Gun System for the Main Battle Tank'. *Military Technology*, No.1, Spring 1977. pp.62-64.
2.36 *Department of Defense Consideration of West Germany's Leopard as the Army's New Main Battle Tank*, Report to the Congress by the Controller General of the United States. General Accounting Office. Washington. November 1977, pp.ii-iii.
2.37 H R Lembcke. 'A Tank of the Future in the Context of German Defense Technology'. *MaK Defense Journal*. No.5, November 1980, pp.20-24.
2.38 R M Ogorkiewicz, *S-Tank*, AFV/Weapons Profile No.28, Profile Publications, Windsor. 1971.
2.39 R M Ogorkiewicz. *Swiss Battle Tanks*. AFV/Weapons Profile No.50, Profile Publications. Windsor, 1972.
2.40 R M Ogorkiewicz, 'Merkava Mark 2'. *International Defense Review*, Vol.18, No.3. 1985. pp.311-317.
2.41 R M Ogorkiewicz, 'Merkava Mark 3'. *International Defense Review*, Vol.22, NO.5, 1989. pp.612'616.
2.42 K Ebata. 'Japan's Type 74 Main Battle Tank', *International Defense Review*, Vol.12. No.9. 1979. pp.1538-1542.
2.43 K Kondo. 'Type 74 MBT and its Development', *The Tank Magazine*. No.5, May 1978. pp.28-57.
2.44 P W Lett. 'Korea's Type 88 comes of Age'. *International Defense Review*, Vol.21, No.1, 1988. pp.41-43.
2.45 RM Ogorkiewicz. 'Engesa's Osorio Battle Tank', *International Defense Review*, Vol.21. No.6. 1988, pp.649-653.

2.10 Selected Bibliography

(Excluding works already listed under References)

British Tanks 1946-1970, Royal Armoured Corps Tank Museum, Bovington Camp, 1973.
The Evolution of British Tanks, School of Tank Technology, Chertsey, 1945.
A J Alexander, *Armor Development in the Soviet Union and the United States*, Report R-1860-NA, Rand Corporation, Santa Monica, 1976.
A K Babadzhanyan, ed., *Tanks and Armored Troops*, Ministry of Defense of the USSR, Moscow, 1970, translation by US Army Tank-Automotive Command, Warren, 1970.
D Crow, ed., *Modern Battle Tanks*, Profile Publications, Windsor, 1978.
G Forty, *Chieftain*, Ian Allan, London, 1979.
C F Foss, ed., *Jane's Armour and Artillery 1988-1989*, 9th Ed., Jane's Information Group, Coulsdon, 1988.
R Hilmes, *Kampfpanzer*, Umschau Verlag, Frankfurt am Main, 1983.
R Knecht, ed., *Leopard Combat Tank*, Lehmanns Verlag, Munich, 1972.
K Macksey, *The Tanks*, Arms and Armour Press, London, 1979.
J Milsom, *Russian Tanks 1900-1970*, Arms and Armour Press, London, 1970.
R M Ogorkiewicz, *Design and Development of Fighting Vehicles*, Macdonald, London, 1968.
S Pugh, *Armour in Profile*, Profile Publications, Leatherhead, 1968.
F M von Senger und Etterlin, *Taschenbuch der Panzer*, Lehmanns Verlag, Munich 1976.
H Stark, *Panzer – Qualität oder Quantität*, Bernard & Graefe, Munich, 1982.
S J Zaloga, *Modern Soviet Armour*, Arms and Armour Press, London, 1979.

Chapter 3

Tank Guns and Ammunition

3.1 Evolution of Conventional Rifled Guns

Weapons mounted in tanks are, inevitably, a function of the targets which they are expected to engage. In the main, these consist of armoured vehicles, weapon emplacements and personnel and they constitute a range of battlefield targets which call for guns and rifle-calibre machine guns. In consequence, both types of weapons have been mounted in tanks, to enable them to engage effectively the whole range of targets. At the same time the two types of weapons have become more effective by being mounted in tanks, because this has made them more mobile.

The characteristics of the ground targets facing tanks have changed relatively little over the years, except for armoured vehicles. In particular, tanks have changed considerably, becoming progressively more difficult targets. As a result, the problem of defeating them has come to dominate tank armament.

At first, of course, few enemy tanks were likely to be encountered and many of the early tanks were only armed with machine guns. This meant that their capabilities were limited to the engagement of personnel. Nevertheless, light tanks armed only with machine guns were still used in numbers at the beginning of the Second World War. However, as tanks became more numerous the need to engage them could not be ignored. In consequence, tanks were armed with anti-tank as well as anti-personnel weapons, in spite of unrealistic, doctrinaire arguments that they should not fight other tanks which persisted almost to the end of the Second World War, particularly in Britain and the United States.

For the first 25 years or so the need to engage other tanks could be met with relatively small calibre guns similar to contemporary, towed anti-tank guns. Like the latter, most tank guns ranged in calibre from 37 to 47mm and fired full-calibre armour piercing projectiles with muzzle velocities of 600 to 850 m/s. But as the armour of tanks increased guns of this kind became inadequate and during the Second World War they were superseded by larger guns having a calibre of 50, 57 and 75 or 76.2mm.

Guns of 75mm had been mounted much earlier in the first French tanks but this was done because guns of that calibre were commonly used at the time and not because they were needed against other tanks. However, the 75mm field gun mounted in the St Chamond tank of 1916 fired projectiles with a muzzle velocity of 550 m/s, which made them very effective against the thin armour of the early tanks. In fact, even lower velocity 75mm guns were effective against the early tanks and German tanks of the 1930s, from the *Grosstraktoren* to the early Pz.Kpfw.IV,

were armed with 75mm guns which were only 24 calibres long and fired projectiles with a maximum velocity of 420 m/s. Soviet tanks of the period, such as the T-28 and T-35, had even shorter, 16.5 calibre guns of 76.2mm.

Unlike the smaller calibre guns, those of 75 or 76.2mm also fired high explosive shells which were large enough to be effective against weapon emplacements and similar targets. Thus, when mounted together with machine guns, they enabled tanks to engage effectively all the principal ground targets in their contemporary form. This made them the obvious choice for tanks and by the middle of the Second World War they did, in fact, become the standard type of tank gun.

By then their length and the muzzle velocity of their projectiles were no longer inferior to those of the field guns but had advanced beyond the latter in response to the growing thickness of tank armour. For instance, Soviet T-34 and KV tanks of the period were armed with 76.2mm guns which were 30.5 and then 41.4 calibres long. Similarly, the length of US 75mm guns grew from 31 calibres in the M3 medium tank to 40 in the M4 medium tank, while the German Pz.Kpfw.IV was rearmed with 75mm guns 43 and then 48 calibres long.

The muzzle velocities of the 75 or 76.2mm guns mounted in the T-34, M4 and Pz.Kpfw.IV ranged from 625 to 750 m/s, which was sufficient against the armour of tanks built until then but which became inadequate as tank armour increased further. In consequence, during the latter part of the Second World War tanks were armed with 75 or 76.2mm guns which had higher muzzle velocities. Thus some US M4 medium tanks were rearmed with the British 76.2mm 17-pounder gun which was 58 calibres long and had a muzzle velocity of 880 m/s. The German Panther was armed with the 7.5cm KwK 42, which was 70 calibres long and had a muzzle velocity of 935 m/s.

This approached the limit of what was practicable in terms of increasing the muzzle velocity of conventional armour piercing projectiles and, therefore, of what could be done with 75 or 76mm guns. In consequence, from the middle of the Second World War onwards tanks have been armed with large calibre guns. The first notable example of this was the German Tiger I of 1942, which was armed with the 8.8cm KwK 36. Next came the Soviet KV 85 and T-34-85 with 85mm guns and then the US M26 Pershing with a 90mm gun. The guns mounted in all these tanks were adaptations of existing anti-aircraft guns, whose calibre and other characteristics happened to match the requirement for more powerful tank guns. Because the various anti-aircraft guns had been developed for essentially the same purpose, they differed little from each other and so did the tank guns derived from them. Thus they were 53 to 56 calibres long and fired armour piercing projectiles with muzzle velocities of 790 to 850 m/s. However, they were followed by guns of a similar calibre but developed specially for tanks. The first of them was the 8.8cm KwK 43 mounted in the German Tiger II, which was 71 calibres long and fired conventional armour piercing projectiles with a muzzle velocity of 1000 m/s.

In the meantime the process of arming tanks with adaptations of large calibre guns designed for other purposes was carried further in Soviet tanks. Thus, the SU-100 tank destroyer and later the T-54 tank were armed with the 100mm D-10 gun which was developed from an earlier naval gun. The IS, or Stalin, tanks were armed with an even larger calibre, 122mm D-25 gun developed from an earlier field gun. The D-25 gun was 43 calibres long and the muzzle velocity of its armour piercing projectiles was no more than 790 m/s, but their mass of 25kg was more than twice the 10.4kg mass of the 88mm gun of Tiger II.

The most powerful tank gun to be put into service before the end of the Second

World War was the 12.8cm Pak 44 mounted in the *Jagdtiger* tank destroyer, which was 55 calibres long and fired 28.3 kg projectiles with a muzzle velocity of 920 m/s. But even more powerful, 150 and 170mm guns were proposed for the *Maus* and E-100 experimental super-heavy tanks which were being developed in Germany between 1942 and 1945. No tank of either type was completed but in the United States similar ideas about the use of large calibre guns led in 1944 to the design of the 65.5 ton T30 heavy tank with a 155mm gun and a prototype of it was actually built in 1947.

The use of guns of 155, let alone of 170mm, presented a number of major problems. They included large recoil forces, which could only be withstood by heavy vehicles, the large size of the ammunition, which restricted severely the number of rounds that could be carried, and, in the absence of automatic loading systems, the difficulty of handling the ammunition because of its weight. The latter was true even when the projectiles and the propellant charges were separate, as they had to be. For instance, the projectiles fired by the 155mm T7 gun of the US T30 tank had a mass of 43kg and their propellant charges had a mass of 18kg, which made them difficult to handle. Even 122 or 128mm guns presented ammunition handling problems and had to have separate projectiles and cartridge cases to reduce the weights to manageable levels.

Some work on 155mm tank guns continued in the United States until 1956 and in 1951-1952 work started in Britain on a tank destroyer mounting a 183mm gun. The ideas underlying this vehicle, which was designated FV 215b, led to the construction of the FV 4005 test bed based on a Centurion tank chassis (3.1). However, no tank was produced during the 1950s with a gun of more than 120 or 122mm, which came to be considered sufficient to defeat the most heavily armoured contemporary tanks. At the same time 120mm guns were recognised to be the largest that it was reasonable to mount in tanks, particularly in view of the limit to the weights which loaders could handle.

Thus, 120mm guns were adopted for a number of heavy tanks which were built during the 1950s. One of them was the US T43, first built in prototype form in 1951 and produced between 1952 and 1954 as the M103 heavy tank. Its design was based on the experience gained with the earlier experimental tanks of 1944 to 1947 and in particular the T32 which was, in effect, a T30 armed with an adaptation of a contemporary 120mm anti-aircraft gun. A noteworthy feature of the M103 was that its turret crew included two loaders, which emphasised the problem of handling the ammunition of 120mm guns, even when the projectiles and the cartridge cases were separate.

The other heavy tanks with 120mm guns were the British Conqueror, which was produced between 1955 and 1959, and the French AMX-50. The first model of the latter, built in 1950, was still armed with a 90mm gun and the second with a 100mm gun but the third, built in 1951, was armed with a 120mm gun. The gun of the AMX-50 was comparable to the M58 (originally T123E1) gun of the US M103 tank, which was 60 calibres long and fired full-calibre 23kg projectiles with a muzzle velocity of no less than 1067 m/s.

However, heavy tanks with 120mm or 122mm guns did not become significant numerically, except for the Soviet IS-3. Total production of the M103 amounted to only 300 and that of the Conqueror to about 180, while the AMX-50 did not advance beyond prototypes. Thus the great majority of tanks continued to be armed with smaller calibre guns.

Apart from the 100mm D-10 guns of the Soviet T-54 and T-55 tanks, the most numerous were the US 90mm guns mounted in the M47 and M48 medium tanks.

These were no longer adaptations of anti-aircraft guns but had been developed specifically for tanks, although they had the same length of 52.5 calibres as the earlier 90mm guns. However, their armour piercing (AP) projectiles had muzzle velocities of up to 915 m/s, compared with 854 m/s of the M3 gun mounted in the M26 tanks. This did not imply any major improvement in their performance against tanks but they were more effective because they were also provided with two other types of armour piercing projectiles. One was of the armour piercing, compositie, rigid (APCR) type with a tungsten carbide penetrator, which could perforate considerably thicker armour than conventional AP projectiles. Similar APCR projectiles had been available for the 90mm M3 gun but they were now fired from the M41 gun with a velocity of up to 1165 m/s instead of 1020 m/s, which resulted in significantly greater armour penetration.

The other type of ammunition was the high explosive anti-tank (HEAT) type with a shaped charge capable of perforating much thicker armour than the AP or even APCR projectiles.

APCR ammunition had been used already in 1941 with the German 50mm tank guns and it had also been developed for the 75 and 88mm guns. However, its use by German tanks was restricted by shortages of tungsten. HEAT ammunition had also been developed during the latter part of the Second World War for German 75 and 88mm guns but its use was even more limited and it did not become important in tanks until it was adopted in the 1950s for the US 90mm guns.

In contrast to the US policy, neither type of ammunition was adopted for the British tank guns developed after the Second World War. The first of them, which

Fig. 3.1 British Challenger, the most recent example of a tank with a rifled gun. (MVEE, Crown Copyright Reserved)

still carried the archaic designation of 20-pounder, had a calibre of 83.8mm. Its design followed that of the German 8.8cm KwK 43 in a number of respects, including a length of 66.7 calibres and the ability to fire conventional, APCBC projectiles with a velocity of 1020 m/s. However, the latter were little used. Instead, the 83.8mm gun was provided with a new type of armour piercing, discarding sabot (APDS) ammunition. Its performance, like that of APCR ammunition, was based on tungsten carbide penetrators but it did not fall off equally rapidly with range. This type of ammunition was first used in 1944 with the 57mm 6-pounder guns of Churchill infantry tanks and shortly afterwards it also began to be used with the 76.2mm 17-pounders. At that stage its velocity was no more than 1200 m/s but with the 83.8mm gun it rose to 1465 m/s, which was higher than that of any other type of tank gun ammunition developed until then and resulted in considerably greater armour penetration.

The 83.8mm gun was introduced in 1948 in the Centurion Mark 3 tank and its use of APDS ammunition was followed by the development of similar ammunition for the 120mm gun of the Conqueror heavy tank. This was done in spite of the fact that the gun of the Conqueror was a derivative of the US 120mm gun developed for the M103 heavy tank, which was designed to fire AP rather than APDS projectiles. The Conqueror's L1A1 gun also differed from earlier tank guns in not being provided with conventional high explosive (HE) ammunition. Instead it fired high explosive squash head (HESH) ammunition, which lacks the fragmentation effect of HE shells but is more effective against tank armour as well as concrete structures.

The same combination of APDS and HESH ammunition was adopted for the 105mm L7 tank gun which was developed directly from the 83.8mm gun. In fact, the original version of the 105mm gun was made in 1954 by reboring an 83.8mm gun and it retained the same chamber volume as the latter. In spite of this it fired a heavier, 5.8kg APDS projectile with a slightly higher muzzle velocity of 1480 m/s. As a result, its armour piercing performance was not only better than that of the 83.8mm gun but approached closely that of the 120mm L1A1, as well as being superior to that of the 122mm D-25 gun of the Soviet IS-3 tanks firing conventional AP projectiles. At the same time, a complete round of its APDS ammunition weighed only about 18.5 kg, which was considerably less than the weight of the projectile of the 122mm D-25, or of the cartridge case of the 120mm L1A1.

All this made the 105mm L7 the best gun available for tanks during the late 1950s. In consequence it was not only used to up-gun the Centurions of the British Army but also to arm almost every new battle tank designed outside the Soviet Union during the late 1950s and the early 1960s, and even some tanks designed during the 1970s and early 1980s. Among others, it was adopted and produced in the United States for the M60 and then for the M1 tanks as the 105mm M68 gun. In that case the range of ammunition available for it was expanded by the development of a fin-stabilised HEAT round, similar to the one developed earlier for the 90mm US tank guns, which the US Army regarded superior to APDS under some circumstances (3.2).

An exception to the use of the 105mm L7 and of its derivatives was provided by the French AMX-30 tank. This was armed with the 105mm F1 gun developed during the 1950s by the Etablissement d'Etudes et de Fabrications d'Armement de Bourges (EFAB), which was designed to fire HEAT projectiles as its only armour piercing ammunition. The OCC 105 F1 HEAT projectile fired by the 105mm F1 gun was of an unusual nature as its shaped charge was mounted on ball bearings within the body of the projectile in order to minimise the spin imparted to the

charge. In fact, the rotation of the shaped charge did not exceed 20 to 30 revolutions per second and this prevented its armour penetration being degraded by the spin of the projectile body. To help minimise the spin imparted to the shaped charge, the rifling of the gun was given a relatively slow twist of one turn in 25 calibres, compared with one turn in 18 calibres of the 105mm L7 gun, but this made it unsuitable for firing APDS.

The OCC 105 F1 was relatively complicated and expensive to produce and the diameter and mass of its shaped charge was lower in relation to its calibre than those of the fin-stabilised HEAT projectiles. But, being spin-stabilised, it was more accurate than contemporary fin-stabilised HEAT projectiles and its fall of velocity with range was less because of its lower aerodynamic drag. Nevertheless, the solution represented by the 105mm F1 gun and its ingenious shaped charge projectiles proved less effective in the long run than the alternatives based on fin-stabilised HEAT projectiles fired from smooth-bore guns, which do not impart spin to their projectiles.

3.2 Low Pressure Guns

Development of an alternative to conventional rifled guns began in Germany during the latter part of the Second World War and in the first instance led to the 80mm Paw 8H63, a light, towed, smooth-bore anti-tank gun which fired fin-stablised HEAT projectiles similar in shape to mortar bombs with a muzzle velocity of 520 m/s (3.3). Paw 8H63 began to be produced by the end of 1944 and some proposals were made to mount similar guns in armoured vehicles. However, their development in Germany came to an end in 1945.

After the war the idea of a low-pressure gun firing fin-stabilised HEAT projectiles was taken up in Belgium by the Mecar company in the form of its 90mm Energa gun. The latter was first tried during the 1950s on experimental wheeled and tracked armoured vehicles built in Switzerland by Mowag. Subsequently it was mounted in some of the Commando armoured cars produced in the United States by Cadillac Gage but the first large scale use of this type of gun did not come until its development in France, following trials there in the mid-1950s of the Mecar gun.

The guns produced in France by EFAB have also had a calibre of 90mm, like their Mecar forerunner, and shallow splines with a very slow twist to impart a low rate of spin to the projectiles, sufficient only to reduce the effect of any minor asymmetries. However, the fin-stabilised projectiles of the EFAB guns differ from the mortar bomb shape of the Mecar projectiles in being shorter by virtue of having fins as a direct extension of the projectile instead of on a tail boom.

The first of the French 90mm low-pressure guns to be used in quantity was the DEFA 921 A (later 90 F1), which was mounted in AML 90 armoured cars produced by Panhard from 1964 onwards. A similar gun, the 90 F3, firing the same projectiles but with a higher muzzle velocity, was subsequently adopted for the modernisation of the AMX-13 light tanks, the gun being produced by re-boring their original 75mm guns. Other 90mm guns of the same kind as the 90 F1 have also been produced since the mid-1970s in Belgium by Cockerill and in Brazil by Engesa, and a similar 90mm gun has also been produced in Sweden by Bofors.

Most of the 90mm low-pressure guns have been mounted in wheeled armoured vehicles but some have also been used to arm, or to re-arm, light tanks or tracked tank destroyers like the Swedish Ikv 91. The relatively low mass of their 3.65 to

5kg HEAT projectiles, together with a modest muzzle velocity of 750 to 900 m/s result in low firing impulses and this makes it possible to mount them in light vehicles. A good example of this is the 5.5 ton Panhard AML 90. At the same time the shaped charges of their HEAT projectiles can penetrate 320mm of steel armour, or in the case of the Bofors 90mm KV 90 S73, as much as 730mm, which gives them considerable anti-tank capacity. However, they are not powerful enough to serve as the armament of battle tanks, particularly in view of the development of armour protection which is much more effective against shaped charges than conventional steel armour. This is true even of the larger calibre versions, such as the gun developed in France and mounted in the AMX-10 RC wheeled reconnaissance vehicle. The gun is the 105mm F2 (MECA), which fires 5.65kg HEAT projectiles with a muzzle velocity of 1120 m/s. This makes it the most powerful of the low pressure guns but it is still considerably less powerful than the guns of battle tanks, whose fin-stabilised HEAT projectiles have approximately the same muzzle velocity but almost twice the mass.

Prior to the adoption of the low pressure guns firing fin-stabilised HEAT projectiles, there was considerable interest in light armoured vehicles armed with recoilless guns. Such guns could be mounted in very light vehicles but as they require more propellant their ammunition is considerably heavier than that of comparable low-pressure or conventional guns. Moreover, their back blast creates

Fig. 3.2 Swedish Ikv 91 tank destroyer armed with a 90mm low-pressure, smooth-bore gun. (Hägglund & Söner)

danger zones behind them as well as making them very conspicuous when they fire. A number of experimental vehicles armed with recoilless guns was built in France during the 1950s and there was interest in them in Britain and in the United States up to the early 1960s. But because of their disadvantages only two vehicles armed with them entered service. One was the M50 Ontos with six 106mm recoilless rifles which was produced for the US Marine Corps during the 1950s; the other was the Japanese Type 60 with two 106mm recoilless guns, whose production did not end until 1979.

3.3 Smooth-Bore Guns

In the meantime a different type of gun began to be deveveloped for battle tanks. This was a high pressure smooth-bore gun, the development of which was closely connected with that of sub-calibre, arrow-like, fin-stabilised armour piercing projectiles, just as that of low-pressure pseudo-smooth-bore guns developed for light armoured vehicles was closely connected with the development of fin-stabilised HEAT projectiles.

The origins of the arrow-like, armour piercing, fin-stabilised, discarding sabot, or APFSDS, projectiles go back to the work carried out during the Second World War in Germany and in particular at the Peenemünde establishment, where sub-calibre, fin-stabilised projectiles with discarding sabots were developed for several artillery guns to extend their range (3.4). Some thought may have been

Fig. 3.3 US M50 Ontos anti-tank vehicle with six 106mm recoilless guns. (US Marine Corps)

given at that stage to the use of APFSDS projectiles with tank guns but this was not put into effect until the 1950s, when smooth-bore tank guns firing such projectiles began to be developed in the United States. Two of them, the 90mm T208 and the 105mm T210 were mounted in the T95 tank which was being developed between 1955 and 1959 (3.5). Similar developments must have taken place at about the same time in the Soviet Union, as indicated by the appearance in the early 1960s of the T-62 tank with the 115mm U-5TS smooth-bore gun firing APFSDS projectiles.

The smooth-bore tank guns originally developed in the United States were not considered satisfactory because of the large dispersion of their APFSDS projectiles and, in the case of the 90mm T208 gun, because of the entirely separate problems associated with its rigid mounting. However, much better results were obtained with the 120mm Delta smooth-bore gun developed between 1963 and 1965, but abandoned because of the contemporary decision by the US Army to develop the MBT-70 with the 152mm XM 150 gun-missile launcher. The latter was a stretched version of the earlier, short-barrelled 152mm XM 81 gun-launcher and although it was rifled it was made to fire APFSDS projectiles. But the decision to abandon the 120mm Delta gun in 1965 lost the US Army its lead in the development of smooth-bore tank guns.

Wiser views prevailed in Germany where the Rheinmetall Company began to develop smooth-bore tank guns of 105 and 120mm in 1965 (3.6). Firing trials with prototype guns carried out between 1966 and 1969 demonstrated their effectiveness and in 1972 guns of both calibres were mounted in prototypes of the Leopard 2 battle tank.

At the time smooth-bore guns and APFSDS ammunition were still not generally accepted. Objections to them were particularly strong in Britain where in 1973 it was still the official view that APFSDS projectiles had greater dispersion and greater loss of velocity with range than APDS projectiles and were, therefore, inferior to them. This proved untrue but until then the Royal Armament Research and Development Establishment concentrated on the development of rifled guns and of APDS ammunition, with which it had been particularly successful during the previous two decades. Thus, the development of the 105mm L7 gun was followed during the late 1950s by that of the 120mm L11 gun for the Chieftain tank and then, during the late 1960s and early 1970s, of a 110mm gun.

The APDS projectiles of the 110mm gun had a higher than ever muzzle velocity of 1578 m/s but during the trilateral trials carried out in Britain in 1975 their armour penetration proved inferior to that of the APFSDS projectiles not only of the Rheinmetall 120mm gun but also of the 105mm M68 gun, the US version of the British 105mm L7. As a result, British development effort finally switched from APDS to APFSDS ammunition and from 110 back to 120mm guns, but still of the rifled kind.

The argument which has been advanced in favour of rifled tank guns is that they are more versatile, because they can fire all types of conventional, spin-stabilised projectiles and, given slipping driving bands, they can also fire fin-stabilised projectiles. On the other hand, smooth-bore guns can only fire fin-stabilised projectiles. Moreover, some of the projectiles, and in particular high explosive, squash head (HESH) projectiles are somewhat less effective in their fin- than in their spin-stabilised form, because they contain less explosive in relation to their weight due to the parasitic mass of the fins.

Nevertheless, the 120mm Rheinmetall smooth-bore gun was adopted in 1977 for Leopard 2 and subsequently, under the XM256 designation, for the improved,

M1A1 version of the US M1 tank. A similar 120mm smooth-bore gun was also developed in France during the 1970s and, as a result of an agreement between the two countries, it can fire German ammunition. The 120mm Rheinmetall gun has also been adopted for the Japanese TK-X tank. Very similar smooth-bore guns, interoperable so far as their ammunition is concerned with the German and French guns, have also been developed in Italy by OTO-Melara for the Ariete battle tank and in Israel by Israel Military Industries for the Merkava Mark 3. Smooth-bore guns of 125mm have also been developed in the Soviet Union and mounted since the late 1960s in T-64 and T-72 tanks and in their derivatives.

The general trend has clearly been towards guns of 120 or 125mm but the ability of APFSDS projectiles to perforate considerably thicker armour than APDS projectiles led during the late 1960s and early 1970s to the idea that it might be possible to reduce rather than to increase the calibre of tank guns. A consequence of this was the development in the United States of a smooth-bore 75mm gun by Ares and of an even smaller, 60mm smooth-bore gun by the US Army Armaments Command (3.7). The smaller of the two guns did not get beyond test firings but the Ares gun was mounted in 1978 in the High Mobility/Agility (HIMAG) test bed vehicle and then in the High Survivability Test Vehicle – Lightweight (HSTV-L). It was subsequently developed further into the XM274 gun for the Mobile Protected Weapon System – an armoured vehicle light enough to be lifted by helicopter which the US Marine Corps wanted.

However, developments in the armour protection of tanks made such relatively small calibre guns increasingly questionable. In consequence, the US Marine Corps very wisely rejected both the 75mm Ares gun and a long-barrelled version of one of the 90mm low-pressure guns and by 1989 opted instead for a vehicle armed with a low recoil force version of the 105mm M68 tank gun.

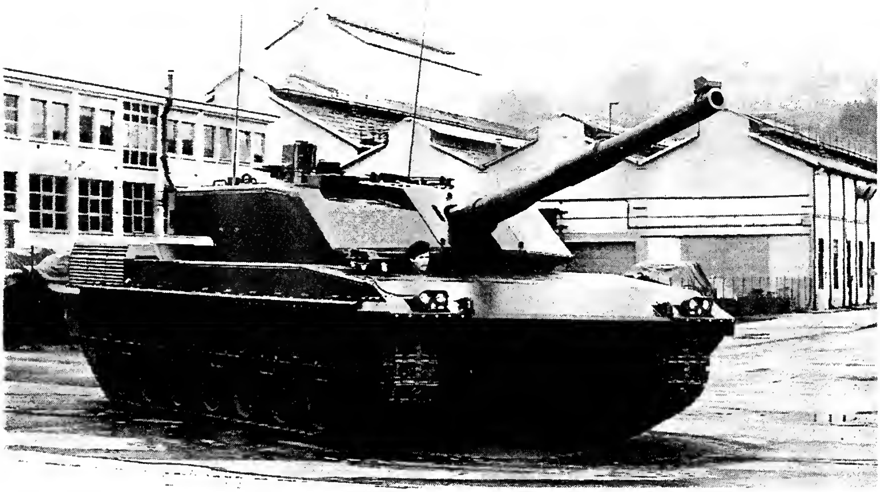


Fig. 3.4 Prototype of the Italian C-1 Ariete battle tank armed with a 120mm smooth-bore gun. (OTO-Melara)

The developments in armour protection have been such that they not only ruled out the possibility of any reduction in the calibre of tank guns but have led to further increases in calibre being considered. Thus, in the early 1980s attention began to be given to arming tanks with guns of more than 120mm and in 1989 agreement was reached by a number of NATO countries that future tank guns should have a calibre of 140mm.

The increases in gun calibre to 120mm which had already taken place were made acceptable by departures from the traditional type of tank gun ammunition with metallic cartridge cases. The earliest of them came with the 120mm L11 gun of the Chieftain tank and involved a separation of the projectile from a bagged or fully combustible case propellant charge. This meant that the loader did not have to handle more than 10kg at any time when loading APDS rounds. However, the ammunition system of the L11 gun requires the use of a third element in the form of an igniter cartridge and of a special breech with an elastic sealing ring.

A much simpler solution was adopted for the Rheinmetall and EFAB smoothbore guns which have one-piece ammunition with semi-combustible cartridge cases. These incorporate a short, metallic stub case with an elastomeric sealing ring which allows the use of a normal sliding wedge type of breech and at the same time significantly reduces the weight of the rounds. Thus, a round of 120mm Rheinmetall APFSDS ammunition has a mass of 19.8kg, which is little more than the 18kg mass of a typical 105mm APFSDS round with the traditional metallic cartridge case. Such rounds can still be handled without undue effort but larger calibre rounds can not, even when they have semi-combustible cartridge cases. Any move towards tank guns with a calibre of more than 120mm is dependent therefore on the availability of suitable loading mechanisms. Such mechanisms have been developed even for guns of 120 or 125mm but for reasons other than simply the weight of their ammunition.

3.4 AP, APCR and APDS Ammunition

Throughout the course of their development tank guns have relied in most cases on the kinetic energy of their projectiles to defeat the armour of the opposing tanks. At first these projectiles took the form of full-calibre, solid, steel shot which was fired at velocities that rose gradually from as little as 412 m/s of the 57mm Hotchkiss 6-pounder gun mounted in the British Mark I tanks of 1916 to 1067 m/s of the M358 projectiles fired from the 120mm gun of the US M103 heavy tank of the 1950s.

A more sophisticated form of armour piercing projectiles used during the same period contained a high explosive bursting charge with a fuze set to detonate it after the projectile had pierced the armour of the target. The armour piercing capability of this kind of AP-HE projectile was somewhat lower than that of the monobloc AP projectiles but, given a perforation of the armour, it was much more lethal because it exploded inside the vehicle. Projectiles of this kind were fired already in 1918 from the 37mm gun of the Renault FT light tank and they were fired from all the German tank guns of the Second World War, accounting for much of their relative effectiveness. The design of some of the German projectiles, and in particular of those produced for the 88mm guns, reached a high degree of refinement with the use of differential hardening of the projectile bodies, so that they combined a high degree of hardness over their front portion with a tough rear section.

By the end of the Second World War, AP and AP-HE projectiles were being

fitted with armour piercing caps, which improved the stress distribution over their noses and thereby reduced their tendency to shatter on impact. They were also being fitted with windshields, or ballistic caps, to reduce their aerodynamic drag and consequently their loss of velocity and penetration with range. If fitted with both caps they became known as 'armour piercing, capped, ballistically capped' (APCBC) projectiles.

Although the various refinements made a significant contribution to the performance of AP, APC and APCBC projectiles, their ability to defeat increasingly thick armour came principally from increases in their muzzle velocity and calibre. However, a practical limit was reached when the calibre rose to around 120mm and muzzle velocity to 1000 m/s, because larger calibre AP projectiles and cartridge cases were too heavy for loaders to handle and because of the high rate of bore wear resulting from the firing of AP projectiles at 1000 m/s. In consequence, the 260mm or so of armour which the German 12.8cm Pak 44 of 1945 could perforate at point blank range and normal impact represented the limit of what could be achieved with AP ammunition fired from manually loaded guns.

The armour of most contemporary tanks was considerably less than this but some, such as the Tiger II heavy tank, already had frontal armour with a horizontal thickness of 300mm. There was therefore a need to increase the thickness of armour which tank guns could perforate. As this could not, for all practical purposes, be achieved with AP projectiles their development was gradually abandoned in favour of other types of kinetic energy ammunition with more effective projectiles.

Thus the 83.8mm 20-pounder was the last British tank gun to be provided with APCBC ammunition, and even then only for a short period. APCBC-HE and APBC ammunition have been used longer with the 90mm guns of the US M47 and M48 tanks, and APBC-HE as well as APCBC-HE ammunition have continued to be used with the 100mm guns of the Soviet T-54 and T-55 and Chinese Type 59 tanks. But no full calibre AP ammunition appears to have been produced for the gun of any battle tank designed since the late 1950s.

The first of the alternative types of kinetic energy projectiles was the armour piercing composite rigid (APCR) shot. This was first developed in Germany at the beginning of the Second World War and was produced for guns ranging in calibre from 37 to 88mm under the designation Pzgr.40. Towards the end of the war this type of ammunition was also produced in the United States for 76 and 90mm tank guns. In the United States it was called 'hyper-velocity armour-piercing' (HVAP), and continued to be used with the post-war generation of 76 and 90mm tank guns. APCR ammunition was also produced during the war in the Soviet Union for guns ranging in calibre from 45 to 85mm.

In essence, APCR projectiles consist of a hard, high-density, sub-calibre core within a light alloy body. In consequence, most of the kinetic energy imparted to an APCR projectile is concentrated in the sub-calibre core and hence on a smaller area of the target. This, together with the high hardness of the core, leads to greater armour penetration than that achieved with full calibre AP projectiles fired from the same gun. The sub-calibre cores or penetrators have been generally made of tungsten carbide sintered using cobalt as the bonding agent or binder, and have had densities ranging from about 14 300 to 16 300 kg/m^3, compared with 7850 kg/m^3 for steel. Tungsten carbide is relatively brittle and as a result penetrators made of it break up as they pierce armour, creating a highly lethal spray of particles. However, the relative brittleness of tungsten carbide penetrators also causes them to fracture when they strike armour obliquely, so that their armour

piercing performance falls off appreciably as the slope of the target armour increases.

Because the mass of APCR projectiles is approximately only half that of AP projectiles they can be fired at higher velocities, up to 1260 m/s having been achieved with conventional guns. But because they are lighter and yet have the same cross sectional area as AP projectiles, their velocity and therefore their armour penetration fall off much more rapidly with range. In consequence, their penetration at longer ranges is little more, or even less, than that of AP projectiles, although it might be considerably greater at short ranges.

The rapid loss of penetration with range caused APCR to be abandoned since the 1950s in favour of armour piercing discarding sabot (APDS) projectiles. These resemble APCR projectiles in having high density, sub-calibre penetrators but the latter separate from the projectile bodies, or sabots, after they leave the gun. In consequence, their velocity and penetration fall off far less rapidly with range. They are, however, somewhat more difficult to produce and their discarded sabots are a hazard to friendly troops if they are fired over their heads.

Nevertheless, APDS projectiles came to be widely used. The first were used in 1944 with the 57mm 6-pounder guns of the British Churchill infantry tanks. By the end of 1944 APDS ammunition was also produced in Britain for the 76.2mm 17-pounder tank guns. Its velocity at that stage was 1200 m/s, which was not much higher than the velocity of the APCR projectiles fired from the contemporary German 88mm L/71 guns. But the muzzle velocity of APDS ammunition produced for the 83.8mm 20-pounder, which was introduced in 1948, increased to 1465 m/s. The widely used 105mm L7 gun, which was introduced during the 1950s, fired APDS projectiles with much the same muzzle velocity of 1478 m/s. This represents the highest velocity of APDS ammunition in regular use, except for that fired from the Swedish version of the L7 gun mounted in the S-tank, which has a length of 62 instead of 51 calibres and fires APDS projectiles at just over 1500 m/s. The British 110mm gun had a similarly high velocity of 1578 m/s but it was never put into service and the APDS projectiles of the 120mm L11 gun of the Chieftain have had a muzzle velocity of only 1372 m/s.

At first, the penetrators of APDS projectiles were similar to those of APCR projectiles. In particular, they were also made of tungsten carbide and as a result their armour penetration was reduced considerably by well sloped armour. Tungsten carbide was still used for the penetrators of the early 105mm APDS projectiles such as the L22 but in the L28 version, which was developed in Britain in the mid-1950s and its US M392 counterpart, a tungsten alloy cap was added to the penetrator. The tungsten alloy was less hard but more ductile than tungsten

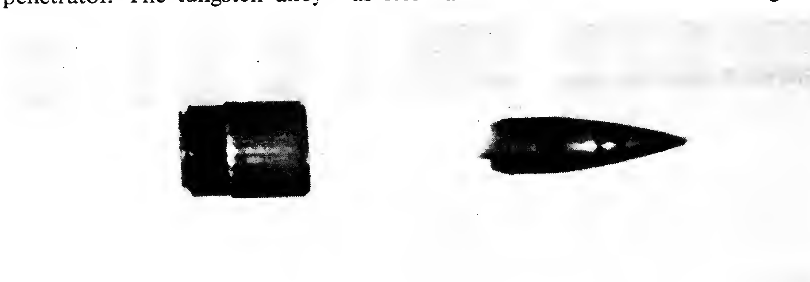


Fig. 3.5 APDS sub-projectile separating from its pot-type sabot.

carbide and the addition of caps reduced the tendency of the penetrators to shatter, improving their armour penetration at other than normal impact. In the early 1960s the performance of APDS projectiles was improved still further with the development in Britain of the L52 projectile, which had a penetrator as well as a cap of tungsten alloy. The L52 was also adopted in the United States where it was produced between 1974 and 1977 as the M728 projectile. It could penetrate 120mm of armour at 60° at up to 1830m, which was almost twice what an APCBC projectile fired from the same gun would have penetrated.

Apart from the materials from which their penetrators were made, the performance of APDS projectiles depended on the mass of their sabots, which absorbed a considerable amount of the kinetic energy imparted by the propellant charges to the projectiles at the expense of the kinetic energy of the penetrators. Efforts were therefore made to minimise the mass of the sabots but the pot-type sabots which were generally used accounted, together with their appendages, for between 21 and 31 per cent of the total mass of the projectiles.

Of the remaining 69 to 79 per cent of the mass, some was due to the sheath in which the penetrators were encased, so that the penetrators themselves accounted for only about 50 per cent of the total mass of the projectiles at launch. Similarly, the outside diameter of the sheath, or the in-flight diameter of the shot, has been equal to around 60 per cent of the calibre of the projectile and the diameter of the penetrators to some 40-odd per cent of it.

Given no new penetrator materials and no reduction in the mass of the sabots because of the stresses which they have to withstand at launch, almost the only way in which the armour piercing performance of APDS projectiles could have been improved further was to concentrate the kinetic energy of their penetrators on a smaller area of the target by increasing their length to diameter ratio. However, spinning projectiles can not have a length to diameter ratio of more than 5 or 6 to 1, and high density, sub-calibre shot of much more than 4 to 1, if they are to be stable (3.8). In consequence, higher length to diameter ratios can only be obtained by abandoning spin stabilisation and adopting instead aerodynamic stabilisation by means of fins.

3.5 APFSDS Ammunition

The development of fin stabilised armour piercing projectiles began in earnest during the 1950s in the United States and apparently also in the Soviet Union. The early US projectiles, such as those fired from the 90mm T208 gun of the T95 tank, had penetrators with a relatively low length to diameter ratio, as indicated by their diameter of 37mm. The penetrators were still made of tungsten carbide, which would not have allowed them to have a high L:d ratio because of its brittleness and which was not, in fact, a very suitable material for them. But the muzzle velocity of 1525 m/s with which the 90mm APFSDS projectiles were fired was already significantly higher than that of contemporary APDS projectiles.

The 120mm Delta gun which followed fired APFSDS projectiles with the even higher velocity of 1675 m/s. Its penetrators still had a relatively low L:d ratio of 8:1 but they could penetrate 300mm of armour, at normal impact, at 1920 m, which demonstrated the superiority of APFSDS over APDS projectiles.

The armour penetration achievable with APFSDS projectiles was apparently considered in the Soviet Union to be such that the BM-6 APFSDS projectile developed during the late 1950s for the 115mm U-5T gun of the T-62 tank did not even have a penetrator of a high density material but only of steel. But its muzzle

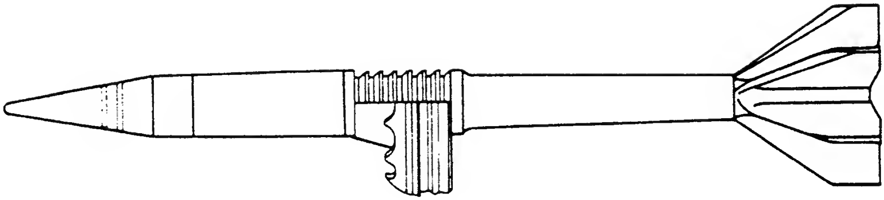


Fig. 3.6 APFSDS projectile of the type fired from Soviet 115 and 125mm guns with its ring-type sabot half-sectioned.

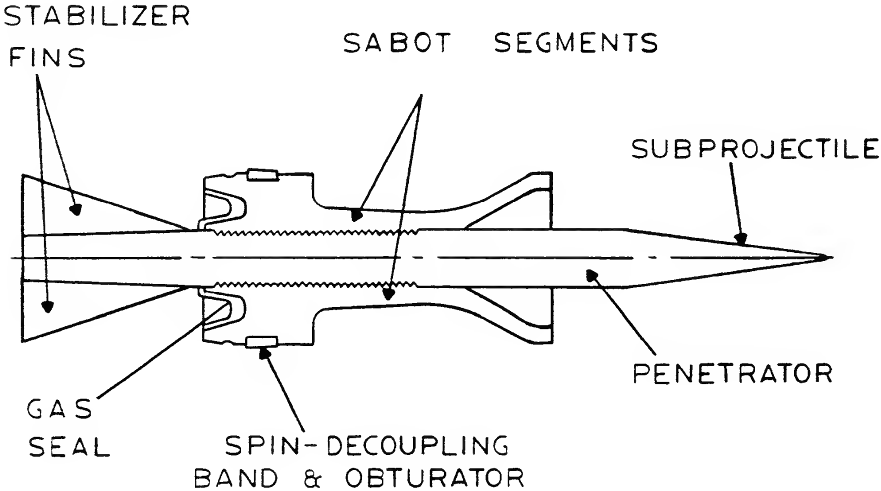


Fig. 3.7 Section through a US XM735E2 APFSDS projectile with a saddle, or spool, type sabot.

velocity was 1615 m/s and it proved capable of penetrating 120mm of armour at 60° at a range of 1900 m, which made it at least as good as the best of the 105mm APDS projectiles (3.9).

Although the armour piercing performance of penetrators made of steel is inferior to that of penetrators of heavy metals, they are less expensive and, because of the greater ductility of steel, they allow shorter length of thread to be used to transfer to them the forces exerted by the propellant gases on the sabots. This was exploited in the design of the 115mm BM-6 projectile, which has a short and

relatively light ring sabot, like the original German Peenemünde artillery projectiles. As a result, the sabot of the BM-6 accounts for only 26.4 per cent of its launch mass.

Other APFSDS projectiles have had aluminium alloy sabots of the saddle, or spool, type which provide greater length of thread for the transfer of forces from the sabot to the penetrator but which are significantly heavier. In fact, saddle-type sabots account for 30 to 39 per cent of the launch mass, their mass increasing with muzzle velocity because of the corresponding increases in the forces acting on the sabots.

On the other hand, saddle or spool type sabots can guide projectiles within barrels without yaw, because of the considerable separation between their two annular bearing surfaces, whereas ring-type sabots can not do this unless they are used in conjunction with relatively large, bore-riding fins. The latter have been used with the BM-6, as well as the early US APFSDS projectiles, with the result that their aerodynamic drag, and hence their loss of velocity with range, have been high. Most recent APFSDS projectiles fired with the use of saddle-type sabots have had much smaller fins and their aerodynamic drag has been consequently lower.

At first APFSDS projectiles were associated exclusively with smooth-bore guns. But the successful use in the United States of the XM578 projectile with the 152mm gun-launcher of the MBT-70 demonstrated that they could also be used with rifled guns. The launching of the fin-stabilised XM578 projectile from a rifled gun was made possible by the use of a slipping driving band, which reduced its rotation to an acceptably low level. In fact, the speed of rotation of APFSDS projectiles fired from rifled guns has been of the order of 30 to 60 revolutions per second, compared with about 780 revolutions per second for typical APDS projectiles such as the US M392 (3.10).

Slipping driving bands had been used before in the United States to fire fin-stabilised HEAT projectiles from rifled guns and they were used even earlier in Germany, albeit only experimentally (3.11). But their use with APFSDS projectiles only started with the XM578, which also demonstrated that the dispersion of APFSDS projectiles could be reduced to the level of APDS projectiles.

The first APFSDS projectile to come into service with a rifled gun has been the US 105mm M735, which began to be developed in 1972 and whose design was derived directly from that of the XM578. It has a 2.21 kg penetrator with a diameter tapering from about 30 to 10mm and like the XM578 a L:d ratio of about 8:1. Its penetrator is of a tungsten alloy but it is still encased in a steel body. Moreover, the fins of the sub-projectile are still relatively large, having a span almost equal to the bore of the 105mm M68 guns from which it is fired at 1500 m/s.

More recently developed projectiles have penetrators with higher L:d ratios, which are reflected in their smaller diameters. For instance, the 105mm L64 projectile developed in Britain has a penetrator with a diameter of 28mm and the OFL 105 F1 developed in France has a diameter of 26mm. Others have penetrators with even smaller diameters in relation to their calibre and L:d ratios as high as 22:1.

There has also been a general move away from encasing penetrators in steel bodies. In its place have come monobloc, one-piece penetrators, which consist essentially of a long rod of a high density metal with a windshield over its front end and, generally, a six-fin tail screwed on to the other end while the middle portion has threads cut out of it to transfer directly the forces from the sabot. The span of

the fins has also been reduced, from the calibre of the projectile to about 70 per cent of it in some cases, resulting in significant reductions in the drag coefficient.

There has also been considerable development of the materials for the penetrators. Most projectiles developed since 1970 have had penetrators made of tungsten-nickel-copper alloys, whose densities have ranged from 17 000 to 18 500 kg/m^3. An example of this is the 105mm L64 projectile whose penetrator is made of an alloy containing 90 per cent of tungsten, 7.5 per cent of nickel and 2.5 per cent of copper. The same alloy was used earlier in the 105mm L52 APDS projectile and it has a density of 17 200 kg/m^3.

Other, more recent projectiles have penetrators made of tungsten-nickel-iron alloys, which typically consist of 90 per cent of tungsten, 7 per cent of nickel and 3 per cent of iron. One example of them is the D23 projectile developed in Germany for the 120mm Rheinmetall gun; another is the NP 105 projectile developed during the early 1980s in Austria by the Ennstaler Metallwerk the penetrator of which is made of a tungsten-nickel-iron alloy having a density of 17 600 kg/m^3.

In the United States the introduction of APFSDS ammunition with tungsten alloy penetrators has been followed by the development of projectiles with penetrators of depleted uranium. This material comes from a waste product of the process of extracting from natural uranium the U-235 isotope which is used in nuclear weapons and at nuclear power stations. The uranium obtained from the waste product is alloyed with up to 0.75 per cent by weight of titanium and the resulting alloy has a density of 18 600 kg/m^3 and good mechanical properties. In addition, depleted uranium has pyrophoric properties, which means that during the penetration of armour particles of the penetrator made of it ignite, setting a target containing any inflammable materials on fire.

Because of its density and mechanical properties, penetrators of depleted uranium can perforate armour more than 10 per cent thicker than that perforated by comparable tungsten alloy penetrators. Depleted uranium has also been less expensive than tungsten alloys. On the other hand, the use of depleted uranium has faced political objections, because of the emotions aroused by its connection with nuclear weapons and of being perceived as a radioactive material. In fact, the radiation level of depleted uranium is very low and there are more serious objections to it on the grounds of its toxicity, although this has been questioned by the producers of depleted uranium (3.12).

In any case, objections or reservations about depleted uranium penetrators have not prevented them being incorporated first in the M774 and then M833 projectiles developed in the United States for the 105mm M68 tank gun and in the XM829 projectile developed for the 120mm XM256 gun.

However, even without the use of depleted uranium, the armour penetration of APFSDS projectiles has been impressive. For instance, the French OFL 105 F1 projectile can penetrate 300mm of armour, at normal impact, at 5200 m, or 370mm at 1000 m, which is considerably more than the penetration of the best of the comparable APDS projectiles. The more recently developed Austrian NP 105 projectile can do better still, even though its muzzle velocity of 1485 m/s is not very different from that of APDS projectiles. In fact, it can penetrate as much as 473mm of armour at normal impact, at 1000m, thanks to its tungsten-nickel-iron penetrator with an L:d ratio of 22:1.

Even better results have been achieved with the APFSDS projectiles fired from the more recently developed German and French smooth-bore guns, not only

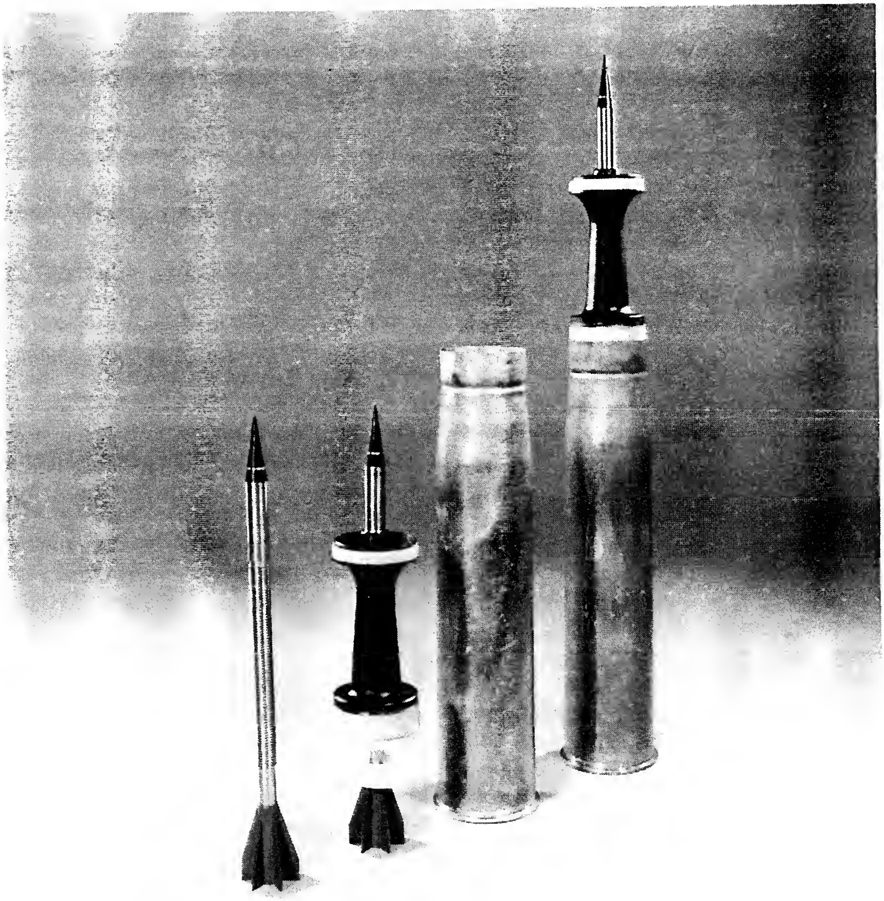


Fig. 3.8 From left, sub-projectile, complete projectile with sabot, cartridge case and complete round of 105mm APFSDS ammunition. (Noricum)

because of their larger calibre of 120mm but also because of their higher muzzle velocity of 1650 m/s, or more.

3.6 Shaped Charge Ammunition

Advances in the armour piercing capabilities of kinetic energy projectiles have been accompanied since the Second World War by comparable progress in the penetration of armour by shaped charge projectiles. Their origins may be traced back to the penetrating effect of hollowed-out explosive charges which had been known for many years in the mining industry and which was described as long ago as 1888 by C E Monroe, after whom it has often been named. However, hollow charges did not become an effective means of penetrating armour until their cavities were lined with metal. This began to be done during the 1930s in Germany, where the importance of the metal liner was first recognised by F R Thomanek. The work there and by H Mohaupt in Switzerland then led to the use

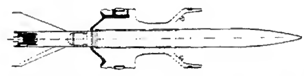
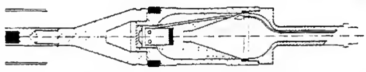
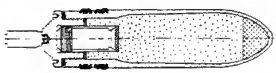
Type of Projectile		V_0 (m/s)	Cartridge length (mm)	Cartridge weight (kg)	Projectile weight (kg)	P max (bar)
Armor-Piercing Discarding Sabot/Fin-Stabilized (APDS-FS)		1,475	941	18	6.3	⩽ 4,200
Multi-purpose (HEAT modified)		1,174	999	21.7	10.3	3,700
High explosive Squash Head (HESH) DM 512		737	929	20.9	11.3	1,800

Fig. 3.9 Principal types of projectiles produced for 105mm rifled tank guns. (Rheinmetall)

of hollow or shaped charges in projectiles as well as anti-tank grenades (3.13).

The first tank gun projectile to incorporate a shaped charge appears to have been the *Hohlladung Granate 38* produced for the 75mm gun of the Pz.Kpfw.IV tanks and introduced into service in 1941. By comparison with later shaped charge projectiles, the performance of the 7.5cm Gr.38 HL was poor, its armour penetration at normal impact being only 80mm, or little more than its calibre, although this was considerably more than that of the conventional, low-velocity armour piercing projectiles fired from the short-barrelled 75mm guns of Pz.Kpfw.IV. Other early shaped charge projectiles were no better. For instance, the 8.8cm Gr.39 HL produced for the 88mm guns had a penetration of only 90mm, which was significantly less than that of the conventional armour piercing projectiles fired from the same guns, even at 3000 m.

The main reason for the relatively low armour penetration of the early shaped charge projectiles was that they were fired from rifled guns, like all other contemporary projectiles. As a result they were spun at a high rate, which was necessary for their stability but which degraded the effectiveness of their shaped charges. The recognition of this fact around 1943 led to the development of fin-stabilised shaped charge projectiles which need very little spin and whose penetration is, therefore, much greater. Thus, a shaped charge projectile of this kind fired from the 80mm Paw 8H63 smooth-bore gun introduced in 1944 could penetrate 140mm of armour, which was equal to 1.75 times its calibre. Similar fin-stabilised projectiles fired from the 90mm Energa gun developed in Belgium after the Second World War did much better still, penetrating as much as 370mm of armour, which equalled 4.1 times their calibre.

To fire fin-stabilised projectiles from conventional tank guns it was necessary to prevent them being spun to any extent by the rifling and this was achieved by the use of slipping driving bands. These began to be developed in Germany towards the end of the Second World War and their development was then continued in the United States where they were first employed on the T300 (later M431) shaped

charge, or HEAT, projectiles developed during the mid-1950s for the 90mm tank guns.

In addition to having a slipping driving band, the 90mm M431 projectiles also represented a considerable advance in the muzzle velocity of shaped charge projectiles, being fired at 1219 m/s. This velocity was considerably higher than that of all earlier shaped charge projectiles and was only made practicable by the development of quicker acting fuzes, which ensured that the shaped charges were detonated rapidly enough, after contact with the targets, to function properly. The higher velocity of the 90mm M431 and of the 105mm M456 projectile based on it increased hit probability but, in common with that of other fin-stabilised shaped charge projectiles, this was still lower than with spin-stabilised projectiles.

The shortcomings of fin-stabilised shaped charge projectiles in this and other respects led to an alternative called the Gessner projectile in Germany and the Obus-G in France, where it was developed and produced. In this the rotation of the shaped charge was minimised not by the adoption of fin-stabilisation but by mounting it on bearings within a spinning projectile body (3.14).

The Gessner or G-projectile was ingenious but it was less efficient than fin-stabilised projectiles, because the diameter and mass of its shaped charge were smaller in relation to its size than those of fin-stabilised projectiles such as the US 105mm M456. In consequence, its use has been confined to the 105mm guns of the AMX-30 and AMX-13 tanks.

But when it was being developed in the late 1950s and early 1960s, the armour penetration of 360mm achieved with the Obus-G was considerably greater than that of the contemporary kinetic energy armour piercing projectiles. As a result, the French Army saw no further need for the latter and adopted the Obus-G in the form of the OCC 105 F1 as the only armour piercing ammunition of its AMX-30 battle tanks. Moreover, the original, gun-armed version of the AMX-30 was to be followed by one armed with a 142mm ACRA gun-launcher which fired guided missiles with shaped charge warheads as its armour piercing ammunition.

A similar trend towards concentration on shaped charge armour piercing ammunition existed around 1960 in the United States where the development of the gun-armed M60A1 tank was followed by that of the M60A2 armed with the 152mm XM162 gun-launcher, which again fired guided missiles with shaped charge warheads as well as shaped charge projectiles. The next tank to be designed, the US-German MBT-70, was also armed with a 152mm gun-launcher but this was of the different, XM150 type which had a longer barrel and was capable of firing APFSDS. These came to be considered necessary in spite of the fact that the Shillelagh missiles fired from the gun-launchers could penetrate about 690mm of armour.

In contrast, the British Army did not adopt shaped charge projectiles for any of its tank guns, mainly because of doubts about their lethality. The doubts were due to the fact that although shaped charges can be designed to perforate very thick armour, when they do the exit diameter of the hole they produce is relatively small and the spray of particles which cause damage behind the armour is confined to a narrow beam. On the other hand, large diameter holes imply the perforation of considerably thinner armour than the maximum that a shaped charge can perforate.

Further and more widespread doubts about the effectiveness of shaped charge weapons arose during the early 1970s as a result of the development of new forms of armour protection, such as Chobham armour, which have proved much more effective against them than homogeneous steel armour. At about the same time the

effectiveness of the kinetic energy type of armour piercing ammunition increased considerably with the introduction of APFSDS projectiles. As a result the relative importance of shaped charge projectiles declined during the 1970s and they came to be regarded as secondary rather than as primary tank gun ammunition.

The change of opinion about shaped charge projectiles occurred in spite of further improvements in their ability to penetrate armour. For example, m/77-2 projectiles developed during the late 1970s for the 90mm gun of the Swedish Ikv 91 tank destroyer have been able to penetrate as much as 730mm of armour, or 8.1 times their calibre.

Other shaped charge projectiles have been improved in different ways. For instance, those of the 120mm Rheinmetall smooth-bore gun have been developed into multi-purpose projectiles, which involved the provision of a more effective fragmentation casing and made them more effective against soft targets. Otherwise the general configuration of the 120mm Rheinmetall HEAT-MP, or multi-purpose, projectiles, and of similar projectiles produced for the 120mm EFAB smooth-bore gun, has followed that of the US M431 and M456 projectiles mentioned earlier. Thus they still have a tail boom with fins and a blunt nose, which helps stability but contributes to a high drag coefficient, and therefore to a rapid loss of velocity with range.

A better projectile from the aerodynamic point of view was developed in France during the late 1960s, although it did not advance beyond experimental firings. This was the 105mm MECA/APX projectile, developed for the 105mm F2 (MECA) gun, which had a pointed nose and slender flip-out fins. It also incorporated rocket assistance which increased its velocity from 1000 m/s at the muzzle to a maximum of 1500 m/s.

Another more efficient configuration was subsequently developed for the US Army by Avco Systems Division in the shape of the XM815 105mm HEAT-MP projectile. Its muzzle velocity of 1174 m/s was the same as that of the M456 projectile which it was designed to replace but, because of the lower drag of its pointed nose body and the stability provided by its slender pop-out fins, it proved significantly more accurate.

3.7 High Explosive Ammunition

The ideal, from many points of view, would be for tanks to fire a single type of ammunition. Unfortunately, none of the different types can meet their needs by itself. For instance, armour piercing ammunition such as APDS or APFSDS has met the need to defeat other tanks but is ineffective against infantry in trenches or even in the open. In consequence, it has had to be complemented by another type of ammunition.

The traditional complement to armour piercing ammunition has been conventional high explosive (HE) shells. Their fragmentation effects and blast make them effective against unprotected or lightly protected targets, including light armour vehicles, and they are also relatively inexpensive. But they are ineffective against heavy armour. They have been gradually abandoned therefore in favour of two other types of ammunition which can compensate to a greater or lesser extent for the relative ineffectiveness of APDS or APFSDS ammunition against other than heavily armoured targets and which, at the same time, are also effective to a varying degree against heavy armour.

Thus, of the battle tanks built since the early 1960s, the French AMX-30, the Swedish S-tank and the Swiss Pz.61 and 68 have still used HE ammunition but of

those introduced since 1970 only the Soviet T-64 and T-72 have had this type of ammunition.

One of the two types of ammunition which have supplanted HE is high explosive squash head (HESH), or high explosive plastic (HEP); the first designation originated in Britain, where this type of ammunition was first developed, while the second is of US origin. HESH projectiles consist of a thin-walled shell filled with a plastic explosive which is squashed on impact against the surface of the target and which is then detonated by a delayed action base fuze. The detonation of the explosive in close contact with armour generates in it stress waves which can cause fracture of the inside surface of the armour followed by the spalling of lethal metal scabs.

HESH ammunition was originally developed in Britain during the latter part of the Second World War for destroying concrete fortifications and it remains the most effective type of ammunition against such targets and buildings. It has also proved relatively effective against homogeneous armour. In fact, during the 1950s it was considered in Britain as a possible replacement for all other armour-defeating types of ammunition and low-velocity 75mm guns firing HESH as their anti-tank ammunition have been mounted in British Scorpion light tanks. However, HESH projectiles can be made ineffective by spaced armour, the outer plate of which prevents the generation in the inner plate of stress waves sufficiently intense to cause spalling. In consequence, HESH ammunition can not be relied upon to defeat enemy battle tanks and it has only been adopted as a complement to APDS, starting with the 120mm L1 gun of the Conqueror heavy tank and the 105mm L7 gun of the upgunned Centurions. HESH, or HEP, ammunition was also adopted in the United States and in Germany when both countries adopted the 105mm L7 gun but neither has developed it for new tank guns, nor has any other country with the exception of Britain.

One of the reasons for the limited interest in HESH ammunition has been that it is not only ineffective against tanks with spaced armour but also lacks the fragmentation required against infantry. It is also more expensive to produce than HE ammunition and has had to be fired at relatively low velocities. In fact, the muzzle velocity of HESH projectiles has been limited by the low strength of their thin-walled shells to less than 800 m/s.

In consequence, HESH has been rejected in favour of the other alternative to HE, HEAT. Compared with HEAT, HESH projectiles have the advantage of greater blast effect and can be equally well spin- or fin-stabilised, whereas HEAT projectiles can only be fin-stabilised if they are to develop fully their armour piercing capabilities, and this has implied a higher degree of ballistic dispersion. On the other hand, fin-stabilised HEAT projectiles are much more effective against heavy armour, even if the latter consists of more than one layer, and if nothing else, their use prevents an enemy from optimising the armour of his tanks against ASPFSDS projectiles. In their recently developed multi-purpose form HEAT projectiles also have greater fragmentation effect. They can also be fired at higher velocities, which means that they enjoy the advantages of flatter trajectories and shorter flight times, even though their loss of velocity with range is somewhat greater.

All this makes HEAT more versatile and superior to HESH as a complement to APFSDS ammunition. In addition to HEAT, HESH and HE, there have also been other types of secondary or tertiary ammunition. These include smoke and illuminating shells and anti-personnel projectiles containing steel balls or flechettes. As a result, some tanks could carry as many as five different types of ammunition. But

this would greatly complicate their operation and in general the number of different types of ammunition has been limited to not more than three. However, given a sufficiently versatile type of secondary ammunition, even a third type of ammunition is difficult to justify, particularly in view of the reduction in the number of rounds carried in tanks caused by the increase in gun calibre. In fact, only two types of ammunition have been produced for some of the latest tank guns such as the 120mm Rheinmetall and EFAB smooth bores, the two being APFSDS and HEAT-MP.

3.8 Liquid Propellant Guns

Development of liquid propellant guns started in the late 1940s in the United States, following the lead taken in Germany during the Second World War in the application of liquid propellants to rockets. It has resulted in two types of guns, namely the bulk-loaded liquid propellant gun and the regenerative injection liquid propellant gun, which differ basically in the method of introducing the propellant into the chamber of the gun. Thus in the bulk-loaded gun all the propellant is pumped or otherwise introduced into the chamber before it is ignited. In the regenerative injection gun the propellant is not pumped into the chamber but into a reservoir separated from the chamber by a piston with injection orifices and combustion is initiated by a separate ignition train, which pressurises the chamber. This forces the piston back, causing some of the propellant to be injected through it from the reservoir into the combustion chamber where it ignites. Then, as that propellant burns, pressure in the chamber rises, forcing the piston to inject more propellant into it.

Liquid propellants are either monopropellants, which are liquids containing both a fuel and an oxidizer, or bipropellants, which consist of a fuel and an oxidizer that are stored and fed into a gun separately. The bipropellants may be hypergolic, which means that they ignite spontaneously when their components come into contact, or non-hypergolic, in which case they require a separate source of ignition. Monopropellants and the non-hypergolic bipropellants can be used with either type of liquid propellant gun but hypergolic bipropellants can only be used with the regenerative injection type of gun (3.15).

The early work in the United States involved experimental guns ranging in calibre up to 90mm and a gun of this calibre was tested in 1951 using a hydrazine fuel and a hydrogen peroxide oxidizer. In general, the early work was concerned with guns with regenerative injection of hypergolic bipropellants taken from rocket technology. However, it ran into difficulties because of the mechanical complexity of the regenerative injection systems and the highly corrosive and toxic nature of the propellants which were used. In consequence, interest shifted in the mid-1950s to bulk-loaded guns using hydrazine monopropellants, which were still toxic and corrosive but to a lesser extent than the propellants used previously. However, the results obtained with bulk-loaded guns were inconsistent and offered no significant advantage in performance over solid propellant guns. All this, together with the contemporary change of policy by the US Army in favour of developing guided missile systems instead of guns, led to work on liquid propellant guns being virtually abandoned in the United States around 1960.

A similar fate overtook the early work on liquid propellant guns in Britain. Started in 1952, it led in the first instance to the construction in 1953 of an experimental, regenerative injection, liquid propellant version of the 83.8mm 20-pounder tank gun. The gun used a hypergolic bipropellant consisting of a

hydrazine fuel and red fuming nitric acid oxidizer, which caused severe corrosion problems. This together with a number of other problems, resulted in a redirection of research effort to bulk-loaded 76.2mm guns using monopropellants. But these failed to offer any significant advantage over solid propellant guns and work in Britain on liquid propellant guns was terminated in 1957.

There was little further interest in liquid propellant guns until the early 1970s when there was a revival of work on them in the United States as a result of the development of new monopropellants. These were pioneered by the US Navy as torpedo fuels and were based on hydroxyl ammonium nitrate (HAN) with water as a solvent and diluent. They were much more attractive than the earlier liquid propellants because of their low toxicity, low flammability and low susceptibility to detonation, in addition to their relatively high density of 1400 kg/m^3. In fact, some of the water soluble monopropellants proved hard to ignite under normal atmospheric conditions and would only support combustion if their pressure were raised well above atmospheric, which would only happen in the chambers of guns under normal circumstances (3.16). They were therefore regarded as potentially less vulnerable than solid propellants.

During the mid-1970s an attempt was made to exploit the advantages of the then newly developed monopropellants by using them in a bulk-loaded high velocity 75mm tank gun. Development of this gun became part of the contemporary High Mobility-Agility Programme and was expected to become a successor to the 75mm ARES gun which was being developed under it. But development of the 75mm liquid propellant gun ran up against the fundamental difficulties associated with the combustion of a liquid propellant which is bulk-loaded, as it was in this case. These difficulties arise out of the formation within the liquid in the chamber of a gun of a column of gas, known as the Taylor cavity, which causes unstable combustion and of the subsequent mixing of the gas stream with the remaining liquid, which leads to the creation of a Helmholtz instability. The instabilities inherent in bulk-loaded gun systems result in variable ballistics, as well as variabil-

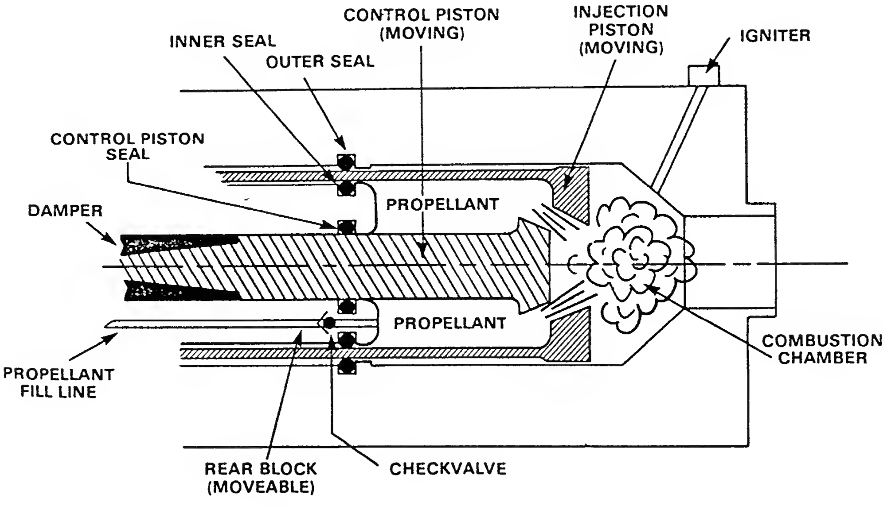


Fig. 3.10 Diagrammatic cross section of the breech of a liquid propellant gun with regenerative injection. (General Electric)

ity in chamber pressures from round to round and severe pressure waves in the chamber (3.17). As a result, there has been little further interest in bulk-loaded liquid propellant guns in spite of their potential advantage of relative simplicity.

Instead, attention has turned since the 1970s to regenerative injection guns. Interest in them was revived by the progress made since 1974 in the United States by the General Electric Company with gun systems using regenerative injection of monopropellants. In the first instance this involved small calibre gun fixtures of up to 30mm but by 1977 development progressed to a 105mm gun fixture, which began to the fired at full charge in 1983. This was followed by the award of a contract by the US Army for a liquid propellant artillery gun technology demonstrator, which led to the construction of a 155mm gun fixture and the start of firing trials in July 1988.

By injecting the propellant during the combustion cycle regenerative guns avoid the instabilities inherent in bulk-loaded guns and firing of the General Electric 25 and 105mm guns demonstrated that the variability of their muzzle velocities was comparable to that of solid propellant guns (3.18). However, the superior internal ballistics of regenerative injection guns have been obtained at the cost of considerable mechanical complexity involving high pressure dynamic seals, valves and a separate ignition train. There is also a unique hazard associated with regenerative injection guns in the possibility of the propellant in the reservoir behind the injection piston being ignited by compression-ignition if any gas is trapped in it, or by other possible sources of ignition.

On the other hand, in common with bulk-loaded guns, regenerative injection guns enjoy the advantage of high propellant loading densities, which implies smaller chambers, although this tends to be nullified by the bulk of the injection system. They also offer the advantage of reduced bore wear because of the relatively low flame temperatures of HAN-based propellants and this, together with their stoichiometric composition, considerably reduces muzzle flash and secondary blast. The possibility of adjusting the variation of pressure with time offered by regenerative injection, and of reducing thereby the initial acceleration of projectiles, makes it possible to fire acceleration-sensitive guided projectiles with higher muzzle velocities or to reduce the mass of the sabots in relation to that of the penetrators of APFSDS projectiles.

The ability to control the rate of injection also makes it possible to achieve higher average chamber pressures within a given peak pressure limit. This implies higher projectile velocities than those feasible with comparable solid propellant guns. The possible increase is of the order of 5 to 15 per cent but the actual muzzle velocities achieved with all but one liquid propellant gun have been no more than 1700 m/s and therefore no higher than those of the more advanced solid propellant tank guns.

The one exception to this is a two-stage liquid propellant gun with regenerative injection devised by General Electric which exploits the travelling charge concept. In this gun only one half of the charge is burnt in the chamber; the rest burns as it moves with the projectile. The result of this is considerably higher muzzle velocities for a given propellant mass, the increase over comparable solid propellant guns and charges being of the order of 30 per cent at velocities of about 2500 m/s. Muzzle velocities of up to 3000 m/s have actually been achieved with an experimental two-stage 30mm liquid propellant gun built by General Electric to explore the concepts embodied in it.

From the point of view of the installation in tanks, liquid propellant guns enjoy a

significant advantage in the reduced volume occupied by their ammunition, because of the high storage density of liquid propellants. Moreover, liquid propellant cells are not only relatively small but can also be of irregular shape and thus can be located within vehicles in spaces not suitable for other purposes. They can also be located more easily where they are less likely to be hit and away from the crew, which increases its survivability. On the other hand, the liquid propellant has to be pumped from the cells into the gun and this requires a system of pipes, pumps and valves which are susceptible to leakage and the other problems that afflict hydraulic systems.

The greatest advantage claimed for liquid propellant guns has been the lower cost of liquid propellants, which has been estimated to be only about one tenth of the cost, per round, of solid propellants (3.19). More conservative estimates put the ratio of solid to liquid propellant costs at between 4 or 5 to 1.

3.9 Electromagnetic Guns

The use of electromagnetic forces to propel projectiles was considered in France during the First World War and in 1944, in Germany, a 10 gram projectile was actually accelerated in a electromagnetic launcher to a velocity of 1080 m/s (3.20). Further work on electromagnetic propulsion was undertaken in the United States during the 1950s but it was only in the late 1970s that electromagnetic guns began to be regarded as a practical proposition. This followed experiments carried out around 1970 at the Australian National University where an electromagnetic launcher was successfully used to accelerate 3-gram projectiles to 6000 m/s (3.21). This was much higher than the velocity achieved with solid or liquid propellant guns, although not as high as the 9000 m/s or so of similar small projectiles which were fired by then from two-stage light-gas guns. But the latter were confined to the role of laboratory tools whereas electromagnetic launchers were perceived to have much wider possibilities. In consequence, a considerable amount of attention began to be devoted to them and by 1980 this led to their extensive development in the United States. By then electromagnetic launchers had also aroused interest elsewhere and work on them started in other countries, including Britain.

An important outcome of the early work in the United States was the launching in 1983 of a 317 gram projectile at 4200 m/s by the Westinghouse Research and Development Centre. The mass of this projectile was comparable to that of APDS projectiles fired from conventional 35mm guns and showed that electromagnetic launchers were capable not only of accelerating small pellets of a few grams but also real size projectiles.

Subsequent developments resulted in even heavier projectiles being launched. In particular, an electromagnetic launcher built in the United States by Maxwell Laboratories was used in 1988 to accelerate a 1.08 kg projectile to 3400 m/s. This meant that the projectile had a kinetic energy at the muzzle of 6.2 MJ, which was comparable to that of contemporary tank gun projectiles, although not yet of the most powerful of them. An example of the latter are APFSDS projectiles fired from 120mm smooth-bore guns with a muzzle velocity of 1650 m/s which have a kinetic energy of 9.5 MJ.

Most of the progress with electromagnetic launchers has been achieved with one particular type of them, namely the DC rail gun. The basic feature of the rail guns is a direct current accelerator which in its simplest form consists of two parallel conducting rails that are connected to a power source and, at the same time, constitute the sides of the accelerator or launcher bore. When the launcher is used

current flows down one rail and in the opposite direction along the other, passing from one to the other through an armature which slides between them. This generates magnetic fields around the rails which, together with the current flowing through the armature, produce a Lorentz force that accelerates the armature and with it any projectile.

The armature can be solid but, because of the limitations of the electrical brushes which they require, solid armatures have not been considered suitable when projectile velocities are high. The alternative, with which the high velocities have been achieved, are plasma arc armatures. These can be created by a thin foil fuze which flashes into a conductive metal vapour when a high current is passed through it.

The principle of operation of a DC rail gun is evidently simple but in practice it requires very high currents of up to 4 MA or more. The launching of projectiles also requires a considerable amount of power (3.22). However, the power is not required continuously and that which actually needs to be generated can be reduced to more manageable levels by spreading the demand for power during the launching of the projectiles to the power produced during the periods when projectiles are not being launched. To this end power produced by a prime mover is first stored in the form of the kinetic energy of a flywheel, which is then drawn on periodically and converted into pulses of electrical energy or alternatively it is stored in a bank of capacitors.

In the former case the conversion of mechanical into electrical energy is carried out in homopolar generators, which are low voltage DC machines with rotors designed to have sufficient inertia to act as flywheels. They can therefore store the energy supplied by the prime movers and when connected by switchgear produce the short pulses of high current electrical energy required by the rail launchers.

For all this, the power needed by an electromagnetic tank gun would require the prime mover to provide a constant output equal to two or perhaps even four times that of the most powerful tank engines used to date. Even if the power demand were brought down to the level of tank engines by improvements in the energy conversion efficiencies, electromagnetic guns would still require another source of power because the use of tanks' own engines would deprive them, temporarily at least, of their mobility. Moreover, the power requirements of electromagnetic guns are very different in nature from those of vehicle propulsion.

In consequence, an electromagnetic gun would need a separate, dedicated prime mover and, to keep the weight of the whole system within reasonable bounds, the prime mover would need to have an exceptionally high power density. The only suitable candidate would be a helicopter-type gas turbine, which might have a power density of 9 kW/kg and whose weight would, therefore, be acceptable. However, other components of a rail gun system would be considerably heavier because of their relatively low energy density. This applies, among others, to the homopolar generators and to the inductors, which are needed to shape the energy pulses delivered by the generators so that they match the characteristics of the projectile accelerators. Thus the total weight of a rail gun system is likely to be significantly greater than that of a conventional, solid propellant gun.

Nevertheless, for all their mass and volume, rail guns enjoy a number of actual or potential advantages. The most important of them is the ability to accelerate projectiles to much higher velocities than other types of guns. Up to a point, this implies greater armour piercing capability and greater probability of hitting manoeuvring targets because of the shorter time of flight. Rail guns might also allow a considerable simplification of fire control systems if they were used to engage

targets at the commonly encountered battle ranges.

Other potential advantages of rail guns include the smaller size and mass of their projectiles in relation to their kinetic energy, which implies that more projectiles could be stowed in a tank. Smaller projectiles would also be easier to handle by automatic loading mechanisms and there would be nothing to extract after firing. In theory, the loading of projectiles would be further simplified by the open-breech nature of the accelerators. But in practice this is more than likely to be nullified by the need to inject projectiles with some velocity in order to reduce the time of exposure of the accelerator rails to the plasma arc to less than what it would be if they had to be driven by the plasma from standstill, and thereby to reduce the erosion of the rails.

Erosion of the rails by the plasma arc is one of the most serious problems with rail guns and severely limits the number of projectiles which can be fired from any one of them. Major problems are also posed by the switchgear, which has to carry very large currents.

Further development might lead, in some cases at least, to the replacement of homopolar generators by compensated, pulsed, single-phase alternators, or compulsators. Unlike the homopolar generator, the compulsator has been devised specifically for the repetitive generation of power pulses and, as it operates at a higher voltage, it can power accelerators directly. In consequence, the use of compulsators would eliminate the need for inductors and this would bring about a significant reduction in the weight of rail gun systems.

Whichever machine is used to convert mechanical into electrical energy, rail guns have the advantage of smaller recoil forces since there are no propellant gases to accelerate. For the same reason there is no blast or obscuration due to the escape of the propellant gases. On the other hand, the high current pulses of rail guns may

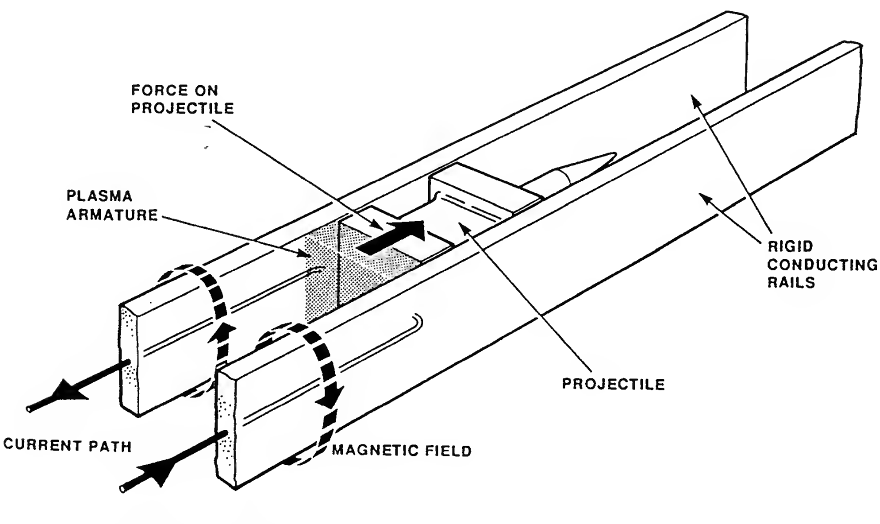


Fig. 3.11 Principle of the rail accelerator of an electromagnetic gun.

give rise to a significant electromagnetic signature and the electromagnetic radiation may constitute a hazard to the crews of rail guns.

The use of high power gas turbines as prime movers of rail guns would also create significant thermal signatures. Moreover, in contrast to conventional guns, the thermal signatures will be created even before rail guns start firing, because their prime movers have to be run up to full power before they can begin to fire. But the use of gas turbines means that the primary sources of energy in rail guns are hydrocarbon fuels, which makes them less vulnerable than conventional guns with their propellant charges. At the same time the calorific value of fuels such as kerosene is 40 MJ/kg, whereas the heat of explosion of even the more energetic conventional propellants is only 5.5 MJ/kg. The higher energy content of the hydrocarbon fuels is offset to some extent by the relatively low thermal efficiency of rail guns, which has been estimated at no more than 7 to 11 per cent. This is less than the thermal efficiency of conventional guns but in spite of this rail guns are likely to use a smaller mass of material per projectile and the fuel they burn costs less than gun propellants.

As an alternative to the launching of projectiles by the interaction of a magnetic field with a current in a rail gun, projectiles can also be launched by the interaction of a travelling magnetic wave with a permanent or induced dipole. This can be done in a number of different coaxial coil AC guns, which incorporate an accelerator with a series of stationary coils around its bore. The coils are energised and couple with the magnetic fields from the currents induced in the projectile to accelerate it along the bore.

A coaxial coil gun is likely to resemble the DC rail gun in deriving its power from a gas turbine and storing it, in the first instance, in the form of the kinetic energy of a flywheel. But the conversion of mechanical into electrical energy would be carried out in a pulsed AC generator and not a homopolar generator. The voltage of the AC generator would be significantly higher and its frequency would also be high, but the currents flowing into the coil accelerator would be less than 300 kA, which is considerably lower than the currents in rail gun systems and to this extent simplifies the design of the switchgear. On the other hand, the electrical circuits of coaxial coil AC guns are considerably more complex.

Against this coaxial coil AC guns offer a very high efficiency of conversion of electrical energy into the kinetic energy of projectiles, which gives them an overall efficiency of more than 50 per cent and a considerable advantage in this respect over rail guns. In principle, it is also possible in them to avoid contact between the projectile and the launcher because of repulsion between them, and this implies low friction and little wear of the launcher bore. The efficiency of coaxial coil AC guns is, however, dependent on the size of their launchers, increasing with their bore.

3.10 Electrothermal Guns

Work on electromagnetic guns has led since the mid-1980s to the development of another category of guns which combine some of their features with those of solid or liquid propellant guns. These are electrothermal guns, which resemble solid or liquid propellant guns in that gases are generated in them to push projectiles through the barrels. In this respect they differ radically from the electromagnetic guns. But they also differ from solid and liquid propellant guns on account of the method by which the propulsion gases are created in them, this being by the interaction of an electrically generated plasma with a working fluid.

Because their projectiles are propelled by gases, electrothermal guns are not subject to the erosion which occurs with electromagnetic guns and their barrels can be much the same as those of conventional guns. At the same time, their working fluids can be selected so that the gases generated from them have a lower mass and, therefore, absorb less energy than the gases of solid propellant guns. But, whatever the working fluid, some energy is still absorbed in accelerating the propulsion gases and to this extent electrothermal guns are less suitable than electromagnetic guns for achieving very high projectile velocities. In fact, they are generally considered most suitable for velocities of up to about 2500 m/s.

Like electromagnetic guns, electrothermal guns require a source of pulses of electrical power, but the amount of electrical energy they need to propel projectiles can be reduced by generating a part of the propulsion energy by the chemical reaction of the working fluid. In consequence, there are two types of electrothermal guns. One might be described as a 'pure' electrothermal gun and derives all of its propulsion energy from the electrical power source. The other type derives some, or even most, of the propulsion energy from the working fluid.

The first type of electrothermal gun uses an inert working fluid such as water. This is heated endothermically by the plasma and vaporises to produce propulsion gases which have a lower molecular weight than those produced by the combustion of solid propellants. However, in this type of gun all the energy required to propel projectiles has to come from the electrical power source, with all the problems that this entails, as it does with electromagnetic guns.

The second type of electrothermal gun uses a reactive working fluid. This can be of a mildly exothermic nature, an example being a slurry consisting of aluminium, titanium hydride and water. When such a slurry is heated by the plasma, chemical reaction between its ingredients produces heat as well as low molecular weight products. As a result, an electrothermal gun using this kind of working fluid not only has the internal ballistic advantage of low molecular weight propellant gases but also requires considerably less electrical energy to propel projectiles than the 'pure' electrothermal guns. In fact, only 30 to 40 per cent of the energy required to propel projectiles may need to come from the electrical power source, the rest being generated by the chemical reaction of the working fluid.

The working fluid can also be of a highly exothermic nature, an example being a mixture of a fuel, such as octane or kerosene, and of hydrogen peroxide. In this case plasma energy is used to vaporise the fuel and mix it with the peroxide to produce a chemical reaction which results in moderate molecular weight products and generates most of the energy for projectile propulsion. The percentage of energy generated by the reaction of the fuel-oxidizer mixture may actually be as high as 80 per cent and this obviously reduces considerably the size of the electrical power plant required with a gun using this kind of working fluid.

Guns using such a high energy working fluid have been developed in the United States since 1986 by FMC Corporation, which has called them 'combustion augmented plasma', or CAP, guns. However, because most of their propulsion energy comes from the fuel-oxidizer mixture, they can also be regarded as bulk-loaded liquid bipropellant guns in which the instabilities associated with bulk-loaded liquid propellants have been suppressed by the flow of the electrically generated plasma.

The plasma which introduces electrical energy into electrothermal guns is generated in a cartridge with a capillary tube containing a wire connected to a blocking electrode at one end and an annular, nozzle electrode at the other end. The wire

explodes when a large surge of current is made to pass through it and this establishes the plasma which flows rapidly out of the capillary into the chamber containing the working fluid.

As in the case of electromagnetic guns, the pulses of electrical power required to generate the plasma can come from a number of sources but they involve only two basically different methods of intermediate energy storage. In one, energy supplied by an engine is stored in the form of the rotational kinetic energy of a homopolar generator or of a compulsator. In the other, electrical energy supplied by an engine-driven alternator is stored in a bank of capacitors, either by charging them directly, or indirectly, through an intermediate battery storage subsystem. With either form of energy storage the pulses of power which are drawn from it have to be suitably shaped in a pulse forming network.

3.11 References

3.1 M C Norman, 'Centurion 5,' in *Armour in Profile*, ed. S Pugh, Profile Publications, Leatherhead, 1968, pp.9-10.

3.2 *Military Operations, Tips for Tankers*, USAREUR Pamphlet No.525-1, HQ US Army, Europe, 1970, pp.29-30.

3.3 *Illustrated Record of German Army Equipment*, Vol.II (Artillery, Part I), War Office, London, 1948.

3.4 *Handbook of Weaponry*, Rheinmetall, Düsseldorf, 1982, pp.530-532.

3.5 J M Warford, 'The T95: A Gamble in High-Risk Technology', *Armor*, Vol.62, No.4, September-October 1983, pp.39-41.

3.6 'The 120mm Smooth Bore Gun System for the Main Battle Tank,' *Military Technology*, No.1, Spring, 1977, pp.62-64.

3.7 'Toward New Combat Vehicle Armament,' *Army Research, Development and Acquisition Magazine*, Vol.22, No.5, September-October 1981, pp.9-11.

3.8 R Reisman, 'The Potential of Sub-Calibered Fin Stabilized Artillery Projectiles,' *Proceedings 1st International Symposium on Ballistics*, Orlando, 1974, pp.III-25 to III-55.

3.9 *HVMS 60mm Weapon System*, Israel Military Industries, Ramat Hasharon, c.1982.

3.10 P A Leonard, 'A Bigger Foot Print,' *Armor*, Vol.87, No.5, September-October 1978, pp.11-13.

3.11 L E Simon, *German Research in World War II*, Wiley, New York, 1947, p.188.

3.12 P Seideman, 'DU: Material with a Future', *National Defense*, Vo.68, No.394, January 1984, pp.29-31 and 76.

3.13 J E Backofen, 'The Weaponization of Shaped Charge Technology', *Proceedings 4th International Symposium on Ballistics*, Monterey, 1978.

3.14 *Handbook of Weaponry*, op.cit., p.524.

3.15 W Witt and K Reinelt, 'Liquid Propellant Charges for Gun and Mortar Ammunition', *International Defense Review*, No.1, 1981, pp.64-66.

3.16 R H Cromer and K E Travis, 'A Review of Some Unique Ignition and Combusion Aspects of Liquid Propellants', *3rd International Symposium on Ballistics*, Karlsruhe, 1977.

3.17 W F Morrison, J D Knapton and G Klingenberg, 'Liquid Propellants for Gun Applications', *7th International Symposium on Ballistics*, The Hague, 1983, pp.63-77.

3.18 W F Morrison, P G Baer, M H Bulman and J Mandzy, 'The Interior Ballistics of Regenerative Liquid Propellant Guns', *8th International Symposium on Ballistics*, Orlando, 1984, pp.IB-41 to 53.

3.19 W F Morrison, J D Knapton and G Klingenberg, op.cit., pp.75-76.

3.20 W Witt and M Loffler, 'The Electromagnetic Gun – Closer to Weapon System Status', *Military Technology*, No.5, 1988, pp.80-86.
3.21 Y-C Thio, 'Electromagnetic Propulsion of Matter to Hypervelocity', *6th International Symposium on Ballistics*, Orlando, 1981, pp.15-28.
3.22 A L Brooks and R S Hawke, 'The Electromagnetic Launcher: A New Weapon?', *6th International Symposium on Ballistics*, Orlando, 1981, pp.29-37.

3.12 Selected Bibliography

(Excluding works already listed under References)

BRL Technology Efforts in ET Gun Propulsion, Vol.1, US Army Ballistics Research Laboratory, Aberdeen Proving Ground, 1988.
Fire and Movement, Royal Armoured Corps Tank Museum, Bovington Camp, 1975.
Illustrated Record of German Army Equipment, Vol.III, Armoured Fighting Vehicles, War Office, London, 1947.
G M Barnes, *Weapons of World War II*, Van Nostrand, New York, 1947.
P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978.
T Cullen and C F Foss, *Jane's Armoured Fighting Vehicle Systems 1988-89*, Jane's Information Group, Coulsdon, 1988.
R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978.
– *Patton*, Presidio Press, Novato, 1984.
– *Firepower*, Presidio Press, Novato, 1988.
R M Ogorkiewicz, *Armour*, Stevens, London, 1960.
F M Von Senger und Etterlin, *Taschenbuch der Panzer 1960*, Lehmanns Verlag, Munich, 1960.

Chapter 4

Ballistics and Mechanics of Tank Guns

4.1 Internal ballistics

Tank guns launch projectiles by using the chemical energy of propellants through the medium of the gases which are produced by combustion of the propellants. Thus, propellant is ignited in the chamber of a gun and as it burns its chemical energy is transformed into the heat energy of the gases which evolve from it. The evolution of the hot gases is accompanied by a rapid rise of pressure in the chamber which, acting on the base of a projectile, drives it down the bore of the gun barrel.

As the projectile begins to move the volume within which the gases are contained increases but, because the propellant continues to burn rapidly for a time, the gas pressure rises further before it begins to fall due to the expansion of the volume. In consequence, peak pressure is usually reached after the projectile has travelled a short distance down the gun barrel and the propellant is all burnt only when the projectile has travelled further still.

The way in which the gas pressure varies with projectile travel affects the velocity with which the projectile is launched because the area under the pressure-travel curve represents the work done by the propellant gases on the projectile per unit of its cross-sectional area, and this equates with its kinetic energy. Thus, to achieve high projectile velocities, the area under the pressure-travel curve should be as large as possible. However, the shape of the curve is severely constrained by several factors. One of them is the level of the stresses that the gun can withstand, which sets a limit to the maximum gas pressure. In principle, the area under the pressure-travel curve could be increased within the pressure limit imposed by the strength of the gun by reducing the rate of burning of the propellant, so that the gas pressure reaches its maximum at a point farther along the projectile travel. This would lead to a more broadly spread pressure-travel curve and consequently to a higher mean pressure for any given maximum pressure. The ratio of the mean pressure to the maximum pressure at the breech is called the piezometric efficiency and the higher it is the lower are the maximum acceleration of the projectile and the pressure the gun must be designed to withstand for any given projectile velocity: the former eases projectile design and the latter reduces the weight of the gun.

But a high piezometric efficiency also means a higher gas pressure when the projectile leaves the gun, which not only implies more blast and muzzle flash but

also more energy remaining in the propellant gases at the expense of the kinetic energy of the projectile. High piezometric efficiency implies therefore that the thermal efficiency of the conversion of the chemical energy of the propellant into the kinetic energy of the projectile is low. To achieve a high thermal efficiency, and the low muzzle pressure that goes with it, the propellant has to be burnt as early as possible during the projectile travel and this, of course, is the opposite of what is required for a high piezometric efficiency.

The total energy available from a propellant is determined from explosion at constant volume in a bomb calorimeter and is commonly called the heat of explosion. Its value per unit mass, or the specific heat of explosion, ranges from about 3000 to 5500 kJ/kg for recently used solid propellants.

However, the energy content of propellants is more often specified by what is variously called their impetus, specific energy, force factor or, misleadingly, force. Whatever the name, it is defined as (4.1),

$$E_p = RT_e \qquad \text{4.1}$$

where R = specific gas constant, $m^2/s^2\,K$

T_e = constant volume, or isochoric, flame temperature, K

The impetus E_p is simply related to the heat of explosion Q_{ex}, because the latter is equal, in effect, to the internal energy of the propellant gases at their isochoric flame temperature, which means that,

$$Q_{ex} = c_v\,T_e \qquad \text{4.2}$$

where c_v = specific heat of the propellant gases at constant volume, $m^2/s^2\,K$

If c_p = specific heat at constant pressure, $m^2/s^2\,K$

then $$c_p - c_v = R \qquad \text{4.3}$$

and $$E_p = Q_{ex}\,(k - 1) \qquad \text{4.4}$$

where $k = c_p/c_v$, the ratio of the specific heats, which for typical propellants has a value of between 1.22 and 1.26.

Thus, if the ratio of the specific heats is known, the impetus of a propellant can be calculated from its heat of explosion. In practice impetus is determined experimentally by burning a known mass of propellant in a constant volume chamber and measuring the maximum gas pressure, from which it can be calculated using an equation of state of the propellant gases. The equation of state commonly used in internal ballistics is the Noble-Abel equation, which is a simpler version of the van der Waals equation. Like the latter, it accounts to a degree for the fact that propellant gases do not behave like a perfect gas and in the case of a constant volume chamber in which complete combustion of the propellant takes place it assumes the following form (4.2),

$$p_m\,(V_c - m_c\eta) = m_c\,R\,T_e \qquad \text{4.5}$$

where p_m = maximum pressure, N/m^2

m_c = mass of propellant, kg

V_c = volume of chamber, m^3

η = covolume of propellant gases, m^3/kg

and $R\,T_e = E_p$, as before.

Covolume is the smallest volume to which a unit mass of a gas can be

compressed and can be determined by firing several different masses of the propellant and measuring the corresponding maximum pressures. For typical propellants it has a value of between 1.0 and 1.2 dm^3/kg, while the impetus ranges from about 800 to 1100 kJ/kg.

Whichever method is used to specify it, the energy released by the combustion of a propellant charge is equal to the sum of the energies imparted or lost to the various components of a gun system when it is fired, i.e.

$$m_c\, Q_{ex} = E_1 + E_2 + E_3 + E_4 + E_5 \qquad \dots\dots\dots \quad 4.6$$

where E_1 = kinetic energy of translation of projectile
E_2 = kinetic energy of propellant gases
E_3 = internal energy of the propellant gases
E_4 = energy lost by heat transfer, mainly to the gun barrel
E_5 = miscellaneous energy losses

The above equation of the conservation of energy provides a basis for computing the variation of the gas pressure with time, or projectile travel, and the muzzle velocity of the projectile. But before this can be computed it is necessary to establish the rate of burning of the propellant and any variation in its burning surface, or what is called form function, as well as the pressure drop between the breech and the base of the projectile, and the magnitude of the heat losses. To do all this various assumptions have to be made and these vary with the degree of sophistication with which the problem is treated.

One assumption commonly made is that the pressure at the breech p_b and the pressure on the base of the projectile p_p are related as follows (4.3),

$$p_b = \left(1 + \varepsilon \frac{m_c}{m_p}\right) p_p \qquad \dots\dots\dots \quad 4.7$$

where m_c = mass of propellant charge, kg
m_p = mass of projectile, kg
ε = fraction of propellant accelerated, commonly taken to be 0.5.

Pressure on the base of the projectile is lower than the breech pressure because of the energy absorbed in accelerating the propellant gases and it decreases as the propellant to projectile mass ratio increases. A good illustration of the difference between breech pressure and projectile base pressure is provided by the results obtained with M735 APFSDS projectiles fired from a 105mm M68 gun (4.4). In this case, under standard conditions, the maximum breech pressure was recorded to be 4150 bar but the maximum projectile base pressure was only 2800 bar, in keeping with equation 4.7.

Of the two it is the pressure at or near the breech which is usually measured and it is the maximum value of the breech pressure which is normally quoted. For low performance guns, such as the 75mm M2 mounted in the US M4 tanks of the Second World War, the maximum breech pressure was 262 MN/m^2, or 2620 bar, the unit in which gun pressures are commonly quoted. Much more recent low performance guns, such as the 76mm L23 mounted in the British Scorpion light tank, have an even lower maximum pressure of 1600 bar and in the French 90mm F1 low-pressure gun the maximum is only 1200 bar. But the demand for high projectile velocities has led to much higher pressures in other guns. For instance, the German 75mm L/70 gun of 1943 already had a maximum pressure of 3200 bar and the widely used 105mm L7, or M68, gun has had a maximum pressure of

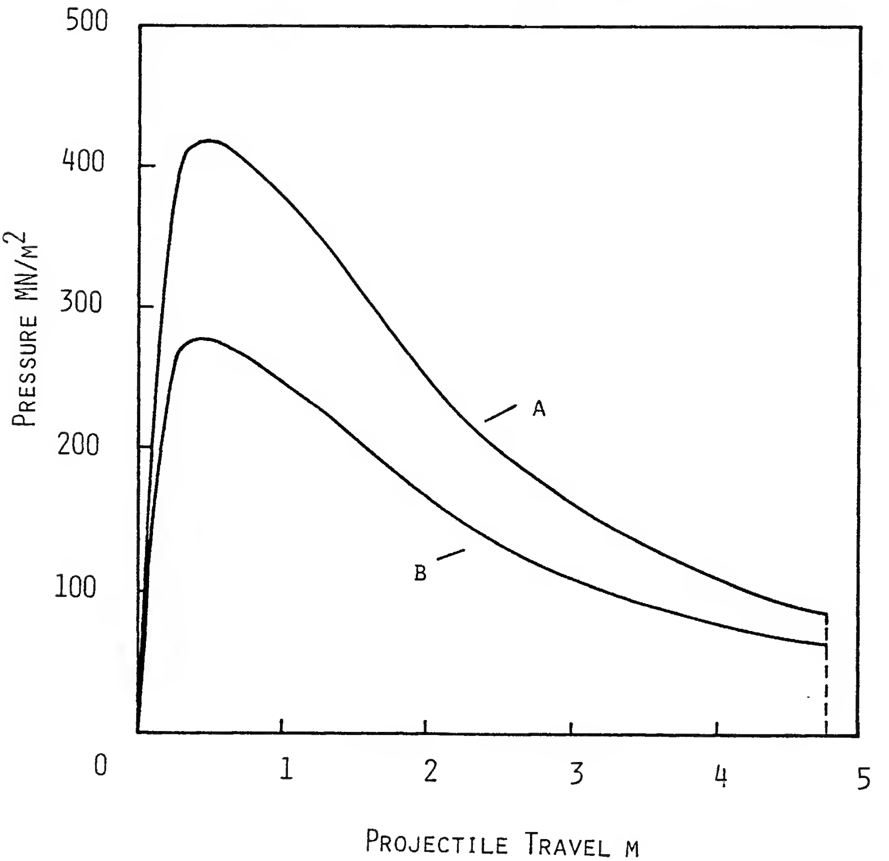


Fig. 4.1 Curves of breech pressure (A) and projectile base pressure (B) versus projectile travel along the bore of a 105mm tank gun.

5100 bar, while the recently produced 120mm Rheinmetall smooth-bore gun has a maximum pressure of 6300 bar.

The maximum breech pressure that is normally quoted corresponds to the highest temperature at which the gun is likely to be fired and which is usually taken to result in a propellant temperature of 50°C. At lower temperatures, which are more likely to be encountered in service, breech pressures are lower and that which corresponds to a propellant temperature of 21°C is generally quoted as the service pressure. Thus for the 105mm L7 gun the breech pressure at 21°C is 4300 bar for the most powerful ammunition fired from it, compared with the 5100 bar at high temperature, which was quoted earlier.

The variations in breech pressure with temperature impose serious limitations on the performance of guns under normal conditions, which are more likely to result in a propellant temperature of 21°C than 50°C. Nevertheless, breech pressure under normal conditions is restricted by what it rises to at 50°C and the fact that the latter is limited by the maximum pressure for which the gun has been or can be designed. In consequence, efforts are being made to reduce the rise in the

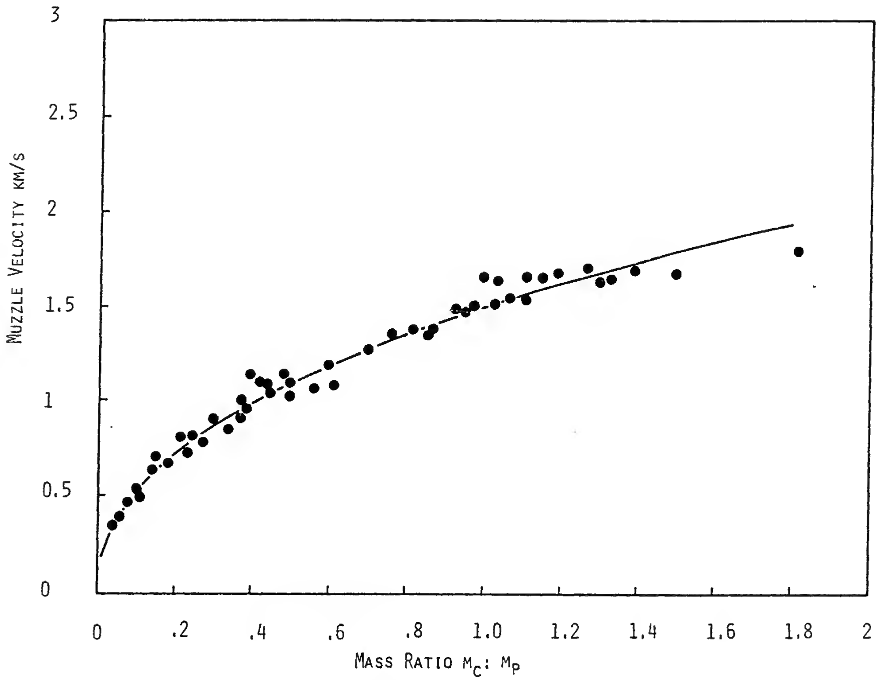


Fig. 4.2 Muzzle velocity of projectiles plotted against their propellant to projectile mass ratio.

rate of burning of propellants with temperature and, hence, the rise with it of the pressure in the chamber (4.5).

The limit to chamber pressures is set by the design gas pressure. This is the maximum chamber pressure which the gun can withstand without permanent deformation and which, obviously, needs to be higher than the maximum breech pressure to allow for a margin of safety. Thus, in the case of the 120mm Rheinmetall smooth-bore gun the design gas pressure is 7100 bar, compared with the previously quoted maximum breech pressure of 6300 bar.

Increases in breech pressure which have taken place over the years have been accompanied by increases in the propellant to projectile mass ratio and, with it, in the muzzle velocity of the projectiles. But as the mass ratio increases the kinetic energy imparted to the projectiles decreases in relation to the energy released by the burning of the propellant. In other words, the ratio of the kinetic energy of the projectile to the chemical energy of the propellant, which is the thermal or ballistic efficiency of a gun, decreases with increasing propellant to projectile mass ratio and by the same token with increasing muzzle velocity. Thus, a disproportionate amount of propellant is required to launch projectiles at high velocities. This is illustrated in Fig. 4.2, which shows a plot of the propellant to projectile mass ratio against muzzle velocity for a number of recently produced guns. The curve drawn through the plot gives an empirical relationship between the muzzle velocity v_0 in metres per second and the mass ratio, which is:

$$v_o = 1500 \left(\frac{m_c}{m_p}\right)^{0.45} \qquad \ldots\ldots 4.8$$

The above is only an approximate relationship because muzzle velocity depends not only on the propellant to projectile mass ratio but also on the specific heat of explosion of the propellant, although the latter does not vary greatly for recently used propellants. For any given maximum pressure it also depends on the expansion ratio: the greater this ratio the more work is done on the projectile by the propellant gases and the higher therefore its muzzle velocity. However, the expansion ratios that can be achieved are limited by the practicable length of gun barrels. In fact, the overall length of tank guns measured from the rear face of the breech block to the muzzle has not exceeded 71 calibres and most recently produced guns have a length of about 50 calibres. Exceptions to this are low performance guns, such as the 76mm L23 gun of the Scorpion light tank, and at the other extreme small calibre automatic cannons, such as the Oerlikon 35mm KDA, whose barrel alone is 90 calibres long.

The expansion ratio of a gun is equal to the sum of the effective volume of the chamber and the volume of the bore divided by the effective volume of the chamber, which is the actual volume of the chamber less that occupied by the cartridge case and any part of the projectile that intrudes into it. Thus, the actual volume of the chamber of the 105mm L7 gun is 7.2 dm^3 but its effective volume is only 6.47 dm^3 when APFSDS projectiles are fired from it. With the bore having a volume of 41.3 dm^3 this gives an expansion ratio of 7.4:1.

For a given chamber volume any increase in the expansion ratio implies an increase in the travel of the projectile and therefore in the work done on it, which is equal to the product of the travel and of the mean pressure acting on the projectile. However, other things being equal, the mean pressure decreases as the expansion ratio increases, so that the amount of work done and, therefore, the muzzle velocity do not increase in proportion to the projectile travel.

As the mean pressure decreases the ratio of it and of the maximum pressure, or the piezometric efficiency, decreases also but the thermal, or ballistic, efficiency increases. A typical value of the latter is provided by the 105mm L7 gun which, firing projectiles with a velocity of 1500 m/s, has a ballistic efficiency of 26 per cent.

At lower velocities the ballistic efficiency exceeds 30 per cent but at higher velocities it is significantly lower, because more energy is absorbed in the kinetic energy of the propellant gases. The rest of the propellant energy is absorbed in the internal energy of the gases, which account for about 40 per cent of it, or is lost by heat transfer, mainly to the gun barrel, which accounts for 15 to 20 per cent of the propellant energy. One per cent, or less, of the energy is absorbed in the rotational kinetic energy of spin-stabilised projectiles and in the kinetic energy of the recoiling mass of the gun. A similarly small amount of energy may be absorbed in forcing the driving band of spin-stabilised projectiles through the rifling.

When muzzle velocity reaches 2000 m/s the ballistic efficiency falls below 20 per cent but an efficiency of 15 per cent was still achieved at the highest velocity reached with a conventional, solid propellant gun, namely 2790 m/s. This velocity was attained in the early 1960s at the Canadian Armament Research and Development Establishment with an experimental 81.3mm smooth-bore gun having a barrel approximately 95 calibres long and an expansion ratio of 8.7:1 (4.6).

In principle, the energy absorbed by the kinetic energy of the propellant gases

can be reduced, and the ballistic efficiency increased, by the use of travelling charges. The latter consist of propellant attached to the base of a projectile which burns as the projectile moves down the bore of a gun barrel ejecting gases at a high velocity and maintaining a high pressure on the projectile. If the velocity of the gases leaving the propellant surface is equal but opposite to the velocity of the surface no energy is wasted on accelerating the gases. In consequence, the ballistic efficiency is greater with travelling charges than with conventional propellant charges and their higher and potentially constant projectile base pressure results in higher muzzle velocities for a given charge mass.

The travelling charge concept was first put forward by H Langweiler and began to be explored in Germany during the Second World War. In 1951 it was taken up in the United States but, after 30 years of intermittent studies and experiments, little progress appears to have been made with it, except with liquid propellant guns, as already mentioned in Section 3.8. With solid propellant guns the principal problem has been to find propellants which burn at the very high rates required for the successful application of the concept and which, at the same time, can be formed into charges strong enough to withstand and to transmit the large forces acting on them (4.7).

4.2 Propellants

Propellants used in tank as well as other contemporary guns are nitrocellulose explosives with various additives. When ignited they undergo rapid decomposition by burning from the surface inwards, which results in the evolution of large volumes of gas. In a gun this creates high pressures which drive projectiles out of the barrels.

Although rapid, the rate of decomposition of propellants is much lower than that of high explosives and they are, therefore, classed as low explosives. In contrast, high explosives detonate, which means that their decomposition is almost instantaneous and accompanied by the formation of shock waves with a high pressure front that travels through the explosive at 2000 to 9000 m/s. Such velocities are much higher than the linear rate of burning of propellants, which is in the region of 10 to 1000 m/s, and makes high explosives unsuitable for propellant charges because the rapidly rising pressures that they generate would burst the barrel of a gun before they could overcome the inertia of a projectile.

How rapidly a particular propellant burns depends on a number of factors, including, of course, its composition and its configuration. In general, tank gun propellants take the form of cylindrical granules, cord or tubular sticks, and the granules may have one or more perforations while the tubular sticks may be slotted. Depending on their geometry the propellant grains are classed as regressive, neutral or progressive, which means, respectively, that their exposed surface area decreases, remains constant or increases as they burn.

Thus, cord propellants are regressive while multi-perforated granular propellants are progressive. Other things being equal, the use of progressive propellants results in higher mean pressures and, therefore, higher muzzle velocities for a given maximum pressure or in a lower maximum pressure for a given velocity. In consequence, there has been a trend to use grains with an increasing number of perforations. Thus, 7 perforations have been commonly used but some recently produced granular propellants have 19-perforation grains and grains with as many as 37 perforations are being tried. Apart from making the grains more progressive, increases in the number of perforations increase the gas permeability of propellant

charges. This minimised the risk of pressure waves being generated during ignition which, in the extreme, can be catastrophic. However, increases in the number of perforations also make production of granular propellants more difficult.

So far as their composition is concerned, conventional nitrocellulose propellants are divided into the three broad categories of single, double and triple-based propellants according to the number of the principal ingredients which they contain. The single-base propellants consist, in essence, of gelatinised nitrocellulose. Double-base propellants contain not only nitrocellulose but also other high-energy constituents, the principal one being nitroglycerine. Their specific heats of explosion range from about 3000 to 5000 kJ/kg, which is greater by about 1000 kJ/kg than the maximum obtained with single-base propellants, but their flame temperatures are also higher and they are apt, therefore, to cause more erosion of the barrels. However, double-base propellants which, in addition to nitrocellulose, contain diglycol dinitrate instead of nitro-glycerine, have lower flame temperatures and are regarded as cool propellants, that is as propellants with flame temperatures of not more than about 3000°K.

Triple-base propellants contain nitroguanidine in addition to nitrocellulose and nitroglycerine or diglycol dinitrate. The amount of nitroguanidine varies from about 25 to as much as 55 per cent, by weight, and its use results in lower flame temperatures and, therefore, less barrel erosion. At the same time the heats of explosion of propellants containing it, which range from about 2900 to 4200 kJ/kg, are comparable to or somewhat greater than those of single-base propellants.

Triple-base nitroguanidine propellants were originally developed in Britain and in Germany during the Second World War and since then they have gradually superseded the earlier, single or double-base propellants in tank guns. One recent example of them is the widely used US M30 propellant which contains 28 per cent of nitrocellulose, 22.5 per cent of nitroglycerine and 47.7 per cent of nitroguanidine. Its other characteristics include a heat of explosion of 4078 kJ/kg, an impetus of 1088 kJ/kg and an isochoric flame temperature of 3040°K.

Other types of propellant developed since the Second World War contain RDX, or hexogen, which is used also as a powerful high explosive. Propellants containing RDX offer higher heats of explosion than more conventional propellants but, in general, high energy propellants have high flame temperatures and cause greater erosion of gun barrels.

To reduce barrel erosion and wear special additives have been developed for use with propellant charges. One of the most successful was developed in Sweden and consists of titanium dioxide and wax. Another type of wear reducing additive which has come to be used consists of a layer of a polymeric material placed between the charge and the inner surface of the cartridge case, which produces a cool gas film that flows along the bore of a barrel and separates the hot propellant gases from the barrel surface.

Whichever propellant is used in a given gun, the velocity which it imparts to a projectile depends on its mass. The maximum muzzle velocity that can be attained with a particular propellant and projectile is therefore a matter of how much of the propellant can be loaded into the chamber of the gun, provided, of course, that the gun can withstand the accompanying pressure. The maximum mass of the propellant that can be loaded depends in turn on its maximum loading density.

Loading density is the ratio of the mass of the propellant charge to the effective volume of the chamber which as already mentioned is the actual volume of the chamber less the volume occupied by the cartridge case and the rear of the

projectile. Even at its maximum, the loading density is considerably lower than the density of the propellant because of the geometry of the propellant grains. Thus the density of conventional propellants is approximately 1600 kg/m^3 but in the case of the slotted tube stick propellant used in the form of bag charges to fire APDS projectiles from the British 120mm L11 gun the loading density has been only 718 kg/m^3. In the case of the cased cord propellant charges used with the APDS projectiles of the 105mm L7 gun the loading density has been 848 kg/m^3 and a very similar loading density of 876 kg/m^3 has been used with cased, 7-perforation granular propellant charges fired with the US M735 APFSDS projectiles from the same type of gun. However, a considerably higher loading density of 948 kg/m^3 has been achieved with a 19-perforation granular propellant charge used with APFSDS projectiles in the French 105mm F1 gun.

Work on consolidated or compacted propellant charges has produced still higher loading densities of more than 1000 kg/m^3 in some cases. The high density charges offer the obvious advantage of higher muzzle velocities with chambers of a given size, or of smaller size rounds. They also offer the advantage of greater ballistic efficiency, because increases in loading density result in reductions in the size of the chambers for a given charge mass and, therefore, higher expansion ratios and more work being extracted from the propellant gases.

4.3 External Ballistics

As projectiles follow their trajectories after leaving the muzzles of guns their velocity decreases steadily because of air resistance. The latter, or aerodynamic drag, varies with the type and the design of projectiles, which should minimise it because falls in the velocity of projectiles increase their time of flight and, therefore, reduces the probability of hitting targets when they are moving, or when there are strong cross-winds. Decreases in velocity also make projectile trajectories more arched, which makes the probability of hitting targets much more dependent on the accuracy of the information about their range and other ballistic parameters. What is more, decreases in the velocity of armour piercing projectiles reduce the kinetic energy on which they depend for penetrating armour.

The aerodynamic drag F_D of projectiles, like that of other bodies, is given by the expression

$$F_D = \tfrac{1}{2}\, C_D\, \rho\, A\, V^2 \qquad \text{4.9}$$

where C_D = drag coefficient, dimensionless
ρ = density of air, 1.225 kg/m^3 at 15°C
A = cross sectional area of projectile, m^2
V = velocity, m/s

The above expression shows that the aerodynamic drag of a projectile depends on its size, velocity and drag coefficient, which, in turn, is a function of its shape and velocity. The variation of C_D with velocity is generally expressed in terms of the Mach number, that is the ratio of the velocity of the projectile to the velocity of sound in air, which is 340 m/s at 15°C. Considered as a function of the Mach number, the drag coefficient remains substantially constant at Mach numbers of less than 1, that is when velocities are subsonic, but rises rapidly to a maximum just above that value and then falls gradually as the Mach number increases further.

The effect of the drag coefficient on the fall in the velocity of projectiles can be

brought out by equating the work done against air resistance to the loss of kinetic energy, which shows that the rate of fall is proportional to it. However, the rate of fall of velocity with distance is also inversely proportional to the sectional density of projectiles, that is the ratio of their mass to their cross-sectional area. In consequence, small calibre projectiles lose their velocity more rapidly than larger calibre projectiles of the same kind and C_D, because the mass of geometrically similar projectiles is proportional to the calibre cubed but the cross sectional area is only proportional to the calibre squared.

Typical values of the cross-sectional density and of the drag coefficient C_{D0} as well as the Mach number M_0 corresponding to the muzzle velocity V_0 are given in Table 4.1 for the different types of projectiles fired from current 105mm tank guns. The table also includes the corresponding initial rates of the loss of velocity with distance $\Delta V/\Delta S$.

The first of the two HEAT projectiles in Table 4.1 is of the heavy, blunt-nose kind similar to the US M456 HEAT projectile while the second is similar to the OCC 105 MECA projectile fired from the French 105mm F2 gun, which has a pointed nose and whose fins are a direct extension of the shell body. The geometry of the HE-FS projectile is similar to the latter and it is also fired from the 105mm F2 gun. The other projectiles in the table are representative of their kind but it should be noted that the drag coefficient of APFSDS projectiles varies considerably with the size of their fins.

4.4 Terminal Ballistics

The interaction between projectiles and the targets at which they are fired has several different facets but the most important of them so far as tank guns are concerned is their penetration and perforation of armour. Penetration is commonly used to describe both aspects of this process but in the context of terminal ballistics it has a more specific meaning which is confined to the entry of a projectile, or penetrator, into the target. Thus, penetration need not necessarily result in the penetrator piercing the target, whereas perforation means that the target has been pierced.

Perforation is the obvious result to aim at, if major damage is to be inflicted behind the armour to the men or equipment which the armour is intended to protect. In this case the damage is achieved by the penetrator which has passed through the armour, or by the fragments into which it breaks up, and by the

Table 4.1 **External ballistics characteristics of typical 105mm gun projectiles**

Type	Mass kg	Diameter mm	Sectional Density kg/m²	V_0 m/s	M_0	C_{D_0}	$\frac{\Delta V}{\Delta S}$ m/s/km
APCBC	17.4	105	2010	1020	3.0	0.28	87
APDS	4.01	61	1372	1475	4.34	0.15	99
APFSDS	3.57	26	6724	1500	4.41	0.35	48
HEAT	10.17	105	1175	1175	3.46	0.46	282
HEAT	5.65	105	652	1120	3.29	0.22	231
HESH	11.26	105	1300	730	2.15	0.64	220
HE	15.5	105	1790	650	1.91	0.31	69
HE-FS	7.2	105	832	800	2.35	0.27	159

spalling of the armour, that is by fragments thrown off the rear face of the armour due to the tensile failure of the material in the region of the perforation. Further and considerably greater damage can be caused behind the armour by the bursting of a projectile containing a high explosive charge. But although they proved very effective in the past, particularly with the guns of the German tanks during the Second World War, armour piercing projectiles containing a bursting charge were gradually abandoned after that conflict because other types of projectiles proved better at penetrating armour.

Damage can also be caused behind armour without perforating it. In particular, the impact of a projectile on the surface of an armour target generates a compressive stress wave which is reflected from the rear surface of the armour and creates tensile stresses that may cause spalling even when there is no perforation. In the extreme, the reflection of the initial compressive stress wave can cause a large flat fragment, or scab, to be thrown off the rear surface of the armour. However, scabbing is generally associated with the detonation of explosive at the surface of armour rather than with armour piercing projectiles which do not perforate the armour.

Scabbing is, in fact, associated mainly with high explosive squash head, or HESH, projectiles and is the mechanism by which they defeat armour protection. But the maximum thickness of homogeneous steel armour which HESH projectiles can cause to scab is not much more than their calibre and this makes them compare unfavourably with other types of projectiles as a means of attacking thick armour. Moreover, they can be defeated more easily than other projectiles by

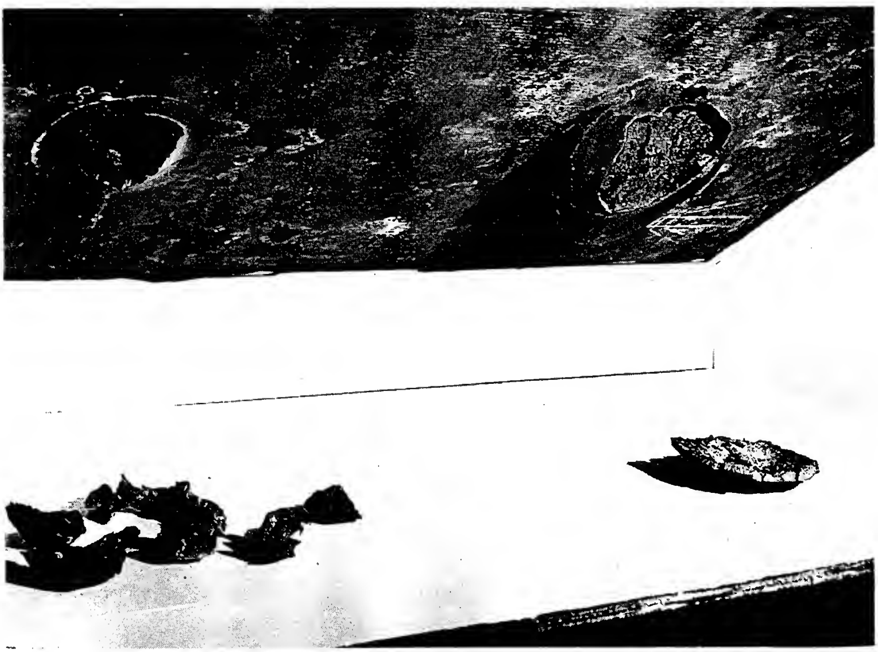


Fig. 4.3 Left, a scab thrown off the back of an armour plate hit by a HESH projectile and, right, spall fragments produced by a perforation by an APDS projectile.

spaced armour. In consequence, HESH projectiles have not been regarded as a very effective type of armour-defeating projectile and they have not been generally adopted, even as a secondary type of tank gun ammunition.

In any case, terminal ballistics of tank guns have been concerned primarily with the penetration and perforation of armour by AP, APDS and, most recently, APFSDS projectiles. The processes involved in penetration and perforation of armour are complex and analysis of them in detail leads to elaborate mathematical models which are only amenable to numerical solutions involving computer programmes. Simple analytical models provide little insight into the process of penetration and their validity is restricted but within their range they can predict penetration or perforation with considerable accuracy (4.8).

The most common example of such a model is the following relationship between the mass, diameter and velocity of a particular type of projectile and the corresponding thickness of a given kind of amour which the projectile perforates at normal impact.

$$\frac{m_p V^2}{d^3} = C\left(\frac{t}{d}\right)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4.10$$

where m_p = mass of projectile, kg
d = diameter of projectile, mm
V = velocity of projectile at impact, m/s
t = thickness of armour perforated, mm
C, n = constants

Equation 4.10 can be derived by dimensional analysis but a similar equation with $n=1$ is obtained directly if the assumption is made that the kinetic energy of a projectile is absorbed in doing work against a constant normal stress, which is compatible with the creation of a hole in armour by lateral displacement of material and is taken to be the hydrostatic pressure required to move the material sideways. Another equation of the same kind but with $n=2$ is obtained by assuming that the kinetic energy of a projectile is absorbed in pushing out of the armour a cylindrical plug of the same diameter as the projectile in the presence of a constant shear stress at the surface of the plug.

Neither of the above hypotheses corresponds exactly to what happens but when equation 4.10 is fitted to the observed results the values of the index n generally fall between 1 and 2. For many years test results were widely considered to be represented by a formula similar to equation 4.10 which was devised around 1886 by J de Marre and which may be written as follows.

$$\frac{m_p V^2}{d^3} = C_1 \frac{t^{1.4}}{d^{1.5}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4.11$$

This dimensionally awkward formula is still quoted as valid in some contemporary texts but, in general, it has been superseded by different forms of equation 4.10. However, because of the similarity, the latter are commonly referred to as de Marre formulae.

There are many different forms of equation 4.10 because the parameters C and n which appear in it vary with the geometry and the material of the projectile and with the armour of the target. They can only be considered as constants, therefore,

when particular projectile and armour combinations are involved. Thus, when the results of firing APCBC projectiles from a gun such as the 83.8mm 20-pounder at rolled homogeneous armour are correlated equation 4.10 becomes:

$$\frac{m_p V^2}{d^3} = 3.7\left(\frac{t}{d}\right)^{1.41} \qquad \text{4.12}$$

However, when the projectile is APDS, such as that fired from the 105mm L7, or M68, gun and again at rolled homogeneous armour equation 4.10 becomes:

$$\frac{m_p V^2}{d^3} = 6.6\left(\frac{t}{d}\right)^{1.37} \qquad \text{4.13}$$

In equation 4.13 the mass and the diameter are not those of the projectile as fired from the gun, or even of it in flight, but the considerably smaller mass and diameter of the high density tungsten penetrator which perforates the armour. Of the mass of the projectile at launch, or its internal ballistics mass, 21 to 31 per cent is accounted for by the sabot, and of the remaining in-flight, or external ballistics, mass 20 to 30 per cent consists of the mass of the penetrator sheath. In consequence, the mass of a typical APDS penetrator amounts to only 54 per cent of the launch mass. Likewise, the in-flight diameter of a typical 105mm APDS projectile is only 60mm and the diameter of its penetrator is 44mm. However, in the case of some highly developed APDS projectiles fired from small-calibre guns, such as the Oerlikon 35mm KDA, the penetrators have a mass equal to as much as 77 per cent of the launch mass.

Similar comments apply to APFSDS projectiles but their sabots account for an even greater percentage of the launch mass than the pot-type sabots of APDS projectiles. The usual APFSDS sabots are of the so-called saddle or, more accurately, spool type and they account for 30 to 40, or even 50 per cent of the launch mass. The relative mass of the sabots tends to increase with the muzzle velocity of the projectiles, because of the need to make them stronger to withstand the correspondingly higher pressures and maximum accelerations of more than 80 000 g. From the point of view of terminal ballistics the mass of the sabots is entirely parasitic, as it absorbs kinetic energy which would be available otherwise for penetrating armour. On the other hand, the mass of the monobloc penetrators of APFSDS projectiles is not much less than the in-flight mass of the projectiles, the relatively small difference between the two being due to the nose shield and the fins.

Correlation of the result obtained with APFSDS projectiles in terms of equation 4.10 produces widely differing values of the parameters C and n, even when the penetrator and target materials are the same, because of the wide variations in the geometry of their penetrators. Attempts have been made to generalise equation 4.10 by rewriting it to include explicitly the ratio of the penetrator length to its diameter but no generally accepted expression has been devised for the dependence of C and n on this ratio. Almost all that can be said about it is that n tends to decrease and C to increase with the length to diameter ratio. This is consistent with the fact that the depth of penetration increases with the length to diameter ratio, which might be expected intuitively because kinetic energy per unit area of the target increases with it.

Because the thickness of armour which can be perforated increases with it, the

length to diameter, or L:d ratio of the penetrators has increased steadily. Thus, the early APFSDS projectile had penetrators with an L:d ratio of about 8:1 but the second generation penetrators introduced during the 1970s have had L:d ratios of between 11:1 and 15:1 while the third generation penetrators introduced during the 1980s have L:d ratios of up to 20:1, or even more.

The higher L:d ratios of their penetrators have made APFSDS projectiles superior to all earlier types of kinetic energy projectile at perforating armour at normal impact but their superiority is even more marked when the armour is struck obliquely, which generally happens in the field. When the impact is oblique the thickness of armour in the path of the projectile becomes greater than its actual thickness, being equal to the latter divided by the cosine of the angle θ which the normal to the surface of the armour makes with the line of flight of the projectile. In consequence, the actual thickness of armour which a projectile can perforate decreases as θ increases and with most projectiles it is proportional to less than θ.

For instance, the thickness of armour perforated by a typical APDS projectile is proportional to $\cos^{1.6}\theta$ and this means that the thickness it can perforate measured in the direction of its flight path decreases with θ. On the other hand, the corresponding thickness perforated by APFSDS projectiles is independent of obliquity, up to $\theta = 70°$ or so. In other words, the actual thickness of the armour which

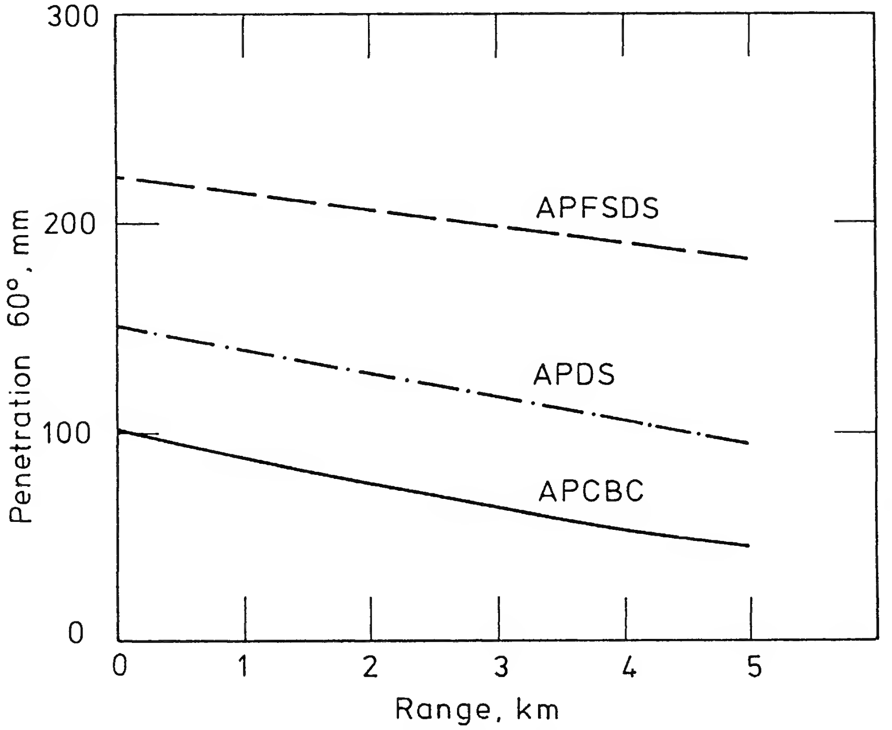


Fig. 4.4 Penetration of steel armour plates inclined at 60° by APCBC, APDS and APFSDS projectiles versus range.

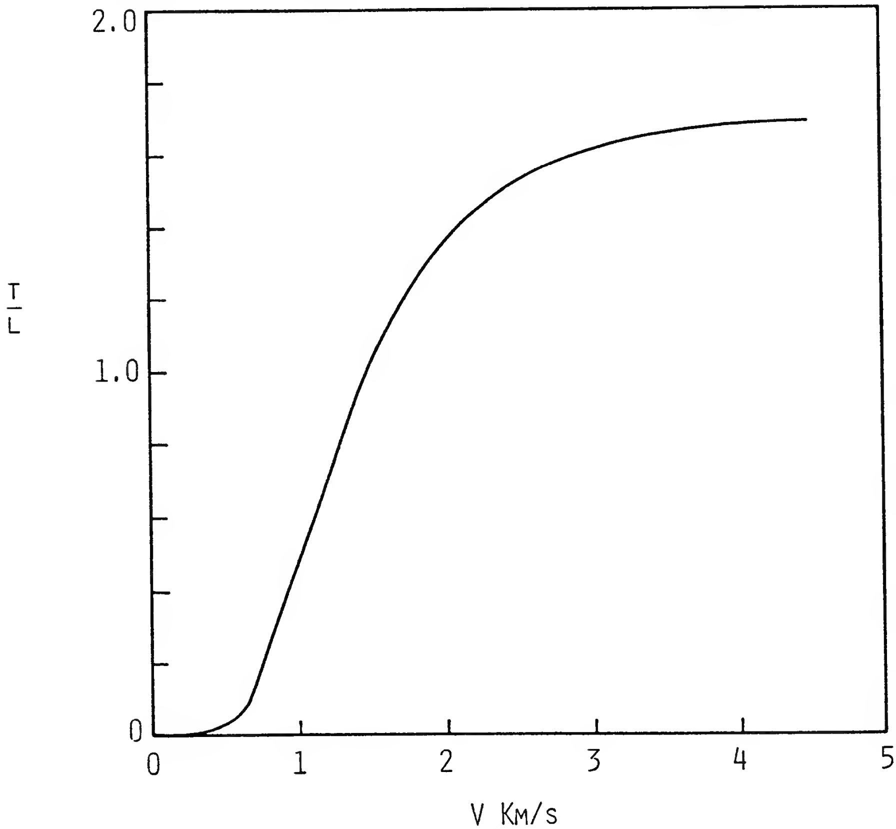


Fig. 4.5 Penetration t of semi-infinite steel targets divided by the penetrator length L plotted against impact velocity V.

APFSDS projectiles can perforate is proportional to cos θ. This makes them as effective against sloping armour as against vertical armour of the same weight, in contrast to all the other kinetic energy projectiles and increases their superiority over the latter.

The overall superiority of APFSDS projectiles over the earlier types of kinetic energy projectiles is illustrated in Fig. 4.4, which shows the variation with range of the thickness of armour perforated at $\theta = 60°$ by APCBC, APDS and APFSDS projectiles fired from the same hypothetical 105mm gun. The superiority of APFSDS is clearly considerable, even though the penetrators implied in the results shown in Fig. 4.4 have an L:d ratio no greater than those of the second-generation APFSDS projectiles.

The perforation of even thicker armour might be expected with penetrators having an L:d ratio increased to 20:1 and of still thicker armour when it is 30:1, which is probably its practical maximum. Otherwise perforation can be increased by increasing the velocity of the projectiles. However, as the impact velocity is increased the nature of the penetration process changes and at very high velocities it becomes hydrodynamic. When this happens the thickness of armour which can

be penetrated is given by an equation similar to that originally derived for the penetration of shaped charge jets and discussed later in connection with them. This equation is:

$$t = L\left(\frac{\rho_p}{\rho_t}\right)^{1/2} \qquad \text{4.14}$$

where ρ_p = density of penetrator material
ρ_t = density of target material

Equation 4.14 means that when penetration becomes hydrodynamic the depth of the penetration is constant for a given penetrator length and penetrator-target material combination. In the case of tungsten alloy penetrators and rolled homogeneous steel armour the ratio of t:L becomes asymptotic to a constant value at velocities of the order of 4000 m/s. This is illustrated in Fig. 4.5 based on the work of Hohler and Stilp on the penetration of tungsten alloy penetrators into semi-infinite targets of homogeneous steel armour, which showed that the ratio of t:L tends to become constant at velocities of the order of 4000 m/s (4.9). However, real targets are of finite thickness and in their case penetration continues to increase at high velocities for a given penetrator length, albeit at a reduced rate (4.10). In this case the increase in penetration is brought about by secondary penetration, or afterflow, which is due to the inertia of the target.

4.5 Penetration by Shaped Charges

Shaped charge, or HEAT, projectiles penetrate armour as a result of the explosive collapse onto its axis of the conical metal liner of a cavity in the charge, which causes a jet of the liner material to be ejected at high velocity out of the cavity. The jet is followed by a slug formed from the rest of the liner material but the latter moves at a much lower velocity and makes no significant contribution to the penetration of the target, which is due to the jet and in particular to its high velocity.

The tip velocities of jets formed by typical shaped charges with copper liners range from about 5000 to more than 8000 m/s. As a result, their impact on a stationary surface gives rise to stagnation pressures of between 1 and 3 Mbar. Such pressures are two orders of magnitude greater than the yield stresses of armour, so that the strength of the latter can be neglected and the penetration of shaped charge jets can be considered in terms of hydrodynamics. In consequence, the jet and the armour are treated as incompressible, non-viscous fluids and their interaction is taken to be governed by Bernoulli's equation. This leads to the expression originally published by Birkhoff, et. al., in 1948 (4.11):

$$\tfrac{1}{2}\,\rho_j\,(V_j - V_p)^2 = \tfrac{1}{2}\,\rho_t\,V_p^2 \qquad \text{4.15}$$

where ρ_j = density of jet material
ρ_t = density of target material
V_j = velocity of jet
V_p = velocity of penetration of target

Hence, assuming steady state conditions and penetration proceeding until the tail end of the jet has entered the target, the total penetration t is given by:

$$t = L\left(\frac{\rho_j}{\rho_t}\right)^{1/2} \qquad \text{4.16}$$

where L = length of jet

In spite of the gross simplifications involved in its derivation, the above equation has been widely used and it indicates fairly accurately the effect on penetration of the jet and target materials' densities. In particular it shows that for maximum penetration of a given target the density of the jet material should be as high as possible. In the great majority of shaped charges the material of the liners, and therefore of the jets, has been copper, which has a reasonably high density of

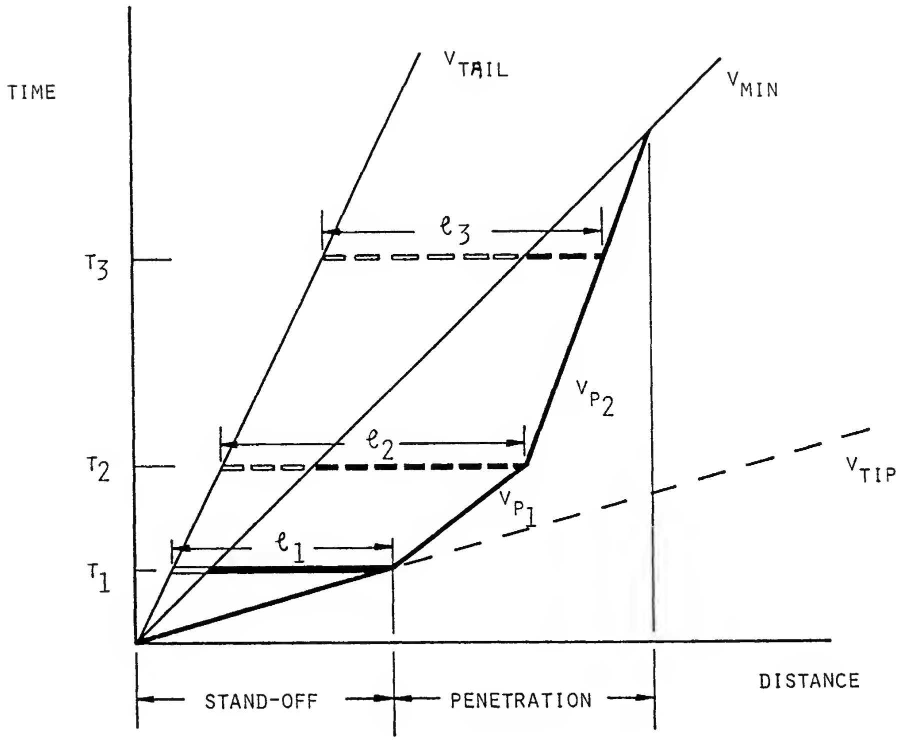


Fig. 4.6 Schematic representation of the formation of a shaped charge jet and of its penetration of a monolithic target, where:
l_1 = length of jet at time t_1 when it reaches target
l_2 = length of jet at break-up time t_2
V_{p_1} = penetration velocity of continuous jet
V_{p_2} = penetration velocity of particulated jet
V_{min} = minimum effective velocity of jet (minimum velocity for penetration)

8900 kg/m^3 and the ductility essential to the formation of elongated, coherent jets. Higher density materials and in particular tantalum, which has a density of 16 600 kg/m^3, have been considered but, although tantalum increases penetration even if it is used only in the form of a thin layer on the inner face of the copper cone, its use has been inhibited by its high cost.

But, although liners have continued to be made of copper, the penetration of shaped charges has increased considerably over the years. The major reasons for this have been improvements in the quality of the liners and in the precision with which the shaped charges are produced. The increases are related to the fact that, contrary to the assumptions of the simple hydrodynamic model, the velocity of the jet varies along its length, with the front travelling faster than the rear, which causes the jet to elongate (4.12). Subsequently the jet breaks up due to the onset of instabilities and the velocity with which it penetrates a target decreases, with the result that its penetration of the target decreases also. But the more ductile the material of the liner and the greater the precision with which the shaped charge is made the more the jet elongates before it starts to break up and the greater, therefore, is its penetration.

However, although penetration is a function of the length of the jet, not all of the jet may be effective. This is due to the fact that the velocity of the tail of a typical jet is only 1200 m/s whereas the minimum velocity which elements of a copper jet need to have to penetrate steel armour is about 2400m/s, which means that the rear portion of the jet does not contribute to the penetration.

The whole process of jet formation and target penetration, together with the influence of the latter on the minimum effective jet velocity, is shown schematically in Fig. 4.6 (4.13, 4.14). As shown in the figure, the jet requires time to stretch to its full length and, because of it, is not fully effective against targets which are close to it. For the same reason penetration increases at first with the distance of the charge from the surface of the target, or the stand-off, which is generally measured from the base of the cone and is normalised by being divided by the diameter of the base. But beyond a certain point, typically after 120 µs, the jet begins to break up and penetration decreases with further increases in stand-off (4.15).

In practice the stand-off is severely restricted by the construction of the shells or missiles which contain the shaped charges, although attempts have been made to overcome this in missiles such as the US TOW by fitting them with long probes. Otherwise a restriction of the stand-off to about two cone diameters has had to be accepted and large penetrations have had to be achieved by other means than detonating shaped charges at optimum stand-off distance.

One way of increasing the penetration has involved the shaping of the detonation wave which is propagated from the explosive charge by inserting a suitably shaped inert material between the booster charge and the apex of the conical liner. This leads to a more effective collapse of the liner and, hence, a higher velocity jet and greater penetration. Other ways of increasing penetration have involved the use of a cylindrical extension at the apex of the liner and variations in the thickness of the liner, which is typically of the order of 2mm.

Variations in the angle of the cone also have an effect on penetration, a total included angle of 20° producing a higher velocity jet and greater penetration than an angle of 60°. However, penetrations produced by liners with small cone angles are also smaller in diameter, which can make them less effective, and jets ejected out of very small angle cavities tend to be unstable. In consequence, shaped charge cones generally have a cone angle of between 40° and 60°.

The fact that penetration increases with decreasing cone angle is in keeping with the simple hydrodynamic theory of shaped charges, according to which the length of a jet produced by the collapse of a conical liner not only stays constant but is equal to the slant height of the cone and, therefore, inversely proportional to the cone angle. A further consequence of it is that, in theory, the penetration of a shaped charge with a particular cone angle is proportional to its diameter and penetration results are, in fact, commonly presented as a multiple of the diameter of the base of the liner cone.

When penetration as well as stand-off are presented in terms of cone diameters the variation of one with the other is as shown in Fig. 4.7, which shows typical curves for three types of shaped charges. The lowest curve is for shaped charges not made to precision tolerances, which was true of them at first. The middle curve is for precision shaped charges developed since the 1960s and the highest curve is for some much more recently developed shaped charges. Development of the shaped charges has clearly increased their penetration from about 4 to more than 6 and, more recently, to 9 cone diameters. But it has also increased the optimum stand-off from about 2 to 8 or 9 cone diameters for the range of shaped charges to which Fig. 4.7 applies.

If a shaped charge is spun its penetration decreases with the speed of rotation, which makes spin-stabilised shaped charge projectiles much less effective than fin-stabilised ones. The rotation of shaped charges in spin-stabilised projectiles can be reduced to a low level by mounting them on ball bearings within the shell body, as in the Obus G, or Gessner projectile. But although this minimises the degradation of the shaped charge by the spinning of the projectile it also reduces the diameter of the charge in relation to the calibre of the projectile and, therefore,

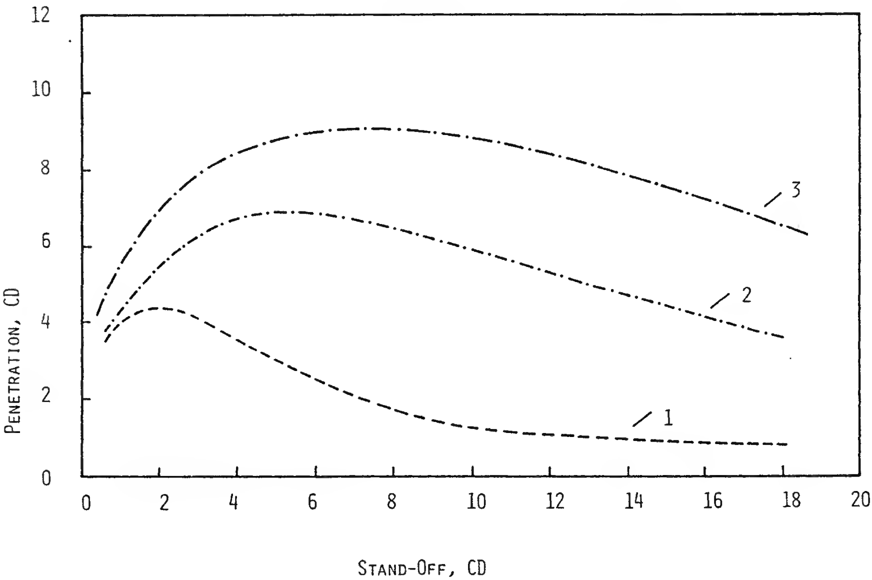


Fig. 4.7 Penetration versus stand-off distance, both in cone diameters, for an early type of shaped charge not made to precision tolerances (1), for a precision shaped charge of the 1970s (2), and for the latest type of shaped charge (3).

its penetration. Even without the double shell construction of the Gessner projectile the diameter of the charge is still significantly smaller than the calibre of the projectile, because of the necessary thickness of the shell body, which reduces it to about 82 per cent of the calibre.

Nevertheless, the penetration of armour by shaped charge projectiles and missiles is very considerable. However, the penetration of armour is not to be equated with the thickness of armour that shaped charges perforate with damaging effect behind the armour, which is their purpose. The reason for it is that the diameter of the hole created by the jet of a shaped charge is relatively small and decreases with the penetration. In consequence, even though a shaped charge may perforate thick armour, the diameter of the exit hole can be so small that it causes little, if any, damage behind the armour. To ensure that this does not happen the shaped charge must not only perforate the armour but must also retain a considerable residual penetration capability, so that the exit hole diameter is large enough for a damaging spray of spall fragments from the penetration. In fact, the degree of damage behind the armour can be correlated with the size of the exit hole, which implies that there is a minimum diameter of the hole that needs to be created to achieve a particular level of damage. However, the hole diameter is not generally specified. Instead, the effectiveness of shaped charges is commonly prescribed in terms of their residual penetration, that is the difference between the depth to which they can penetrate armour and the thickness of the armour which they actually perforate. This margin of performance, which they need to be lethal, has been variously put at up to 150 or 200mm.

4.6 Recoil Forces

The firing of a gun gives rise to forces on the vehicle from which the gun is fired. These forces have to be kept not only below a level at which they could cause the vehicle to topple over but also below that causing excessive vehicle motion and crew discomfort.

The magnitude of the forces which arise with any particular gun can be found by equating the impulse acting on the gun due to the firing of a projectile to the change in the momentum of the projectile and the propellant, which leads to the following equation:

$$I = (m_p V_o + m_c V_G) \qquad 4.17$$

where I = impulse, Ns
m_p = mass of projectile, kg
m_c = mass of propellant charge, kg
V_o = muzzle velocity of projectile, m/s
V_G = average velocity of propellant gases, m/s

The average outflow velocity of the propellant gases V_G varies with muzzle velocity from about 1200 to 1400 m/s and is generally replaced in equation 4.17 by the product of muzzle velocity and a coefficient β. Following the Rheinmetall *Handbook on Weaponry*, β may be taken to vary from approximately 3 at V_o = 400 m/s to 1.5 at V_o = 800 m/s and 1.0 at V_o = 1400 m/s (4.16). Application of equation 4.17 to the case of a typical APFSDS projectile with a launch mass of 5.82 kg and a muzzle velocity of 1500 m/s fired from a 105mm tank gun gives the value of the firing impulse as 16.7 kNs. In the case of the corresponding 105mm

HEAT projectile, which has a lower muzzle velocity of 1174 m/s but a greater mass of 10.3 kg, equation 4.17 gives the firing impulse as 19.5 kNs.

Equating the impulse to the change in the momentum of the recoiling mass of the gun gives the recoil velocity of the latter and hence the kinetic energy of the recoiling mass, which must equal the work done by the recoil system in bringing the recoiling mass to rest. Thus, making the usual assumption that the recoiling mass can recoil freely until the action of the gases ceases and only then begins to be retarded by the recoil system, one gets the following expression for the average force on the gun mounting, or mean trunnion pull as it is commonly called.

$$F_R = \frac{I^2}{2\, m_R\, s} \qquad \ldots\ldots\ldots\ldots \quad 4.18$$

where F_R = average force on the gun mounting, N
m_R = mass of recoiling parts, kg
s = recoil distance, m

For typical tank guns of the 105mm L7 or M68 type, which have a recoiling mass of 1350 kg and a recoil distance of 280mm, equation 4.18 gives the values of the average recoil force as 367 kN, or 37.4 tons, when the previously mentioned APFSDS projectile is fired and as 500 kN, or 51 tons, when the HEAT projectile is fired.

Values of the average recoil force are commonly quoted to characterise guns and to indicate the severity of the forces which they impose on the vehicles that mount them. The magnitude of the average recoil force can be reduced by increasing the recoil distance as equation 4.18 makes clear. In fact, the 280mm quoted above for the 105mm L7 gun is about the minimum recoil distance used with tank guns. The amount of space available within tank turrets allows longer recoil to be used and the Rheinmetall Rh 105-30 gun mounted in the TAM tank developed for Argentina has a recoil stroke of 540mm while the low recoil force version of the 105mm L7 gun developed by Royal Ordnance has a recoil stroke of 760mm. An even longer recoil stroke of 925mm was adopted for the low recoil force version of the same gun developed by Rheinmetall, the Rh 105-11, but this required the gun trunnions to be placed well forward even of a large turret ring and it could not be accommodated in a conventional turret.

Reductions in the average recoil force which result from increases in the recoil distance reduce the stresses in the turret structure and the rest of the vehicle. But increases in the recoil distance do not reduce the firing impulses and it is the latter rather than the average recoil force which govern whether a gun can be mounted in a vehicle without the risk of it moving excessively, or even of overturning when the gun is fired over the side, and without undue discomfort for the crew.

So far as the crew are concerned, there is a rough empirical rule that the ratio of the impulse to the mass of the vehicle should be no more than about 900 Ns/ton. As it happens, for most recently built tanks this ratio has had a value of between 500 and 700 Ns/ton. The few where the ratio exceeded 1000 Ns/ton, as it did in the US M551 light tank when it fired its heavy 152mm HEAT projectiles, have been considered very uncomfortable for their crews.

Firing impulses can be reduced considerably by the use of muzzle brakes, which deflect the gases flowing out of the muzzle and thus create an impulse in the opposite direction to that of recoil. Muzzle brakes were introduced on a large scale during the latter part of the Second World War and they have continued to be fitted

to the guns of light armoured vehicles. But they ceased to be fitted to the guns of battle tanks, mainly because the latter became heavy enough not to require them. A further reason for not fitting them with muzzle brakes has been that their armour piercing ammunition changed from full-calibre AP to APDS and then APFSDS projectiles, which created problems of interference between the discarding sabots and the muzzle brakes. In fact, it was widely thought until the late 1970s that discarding sabot projectiles were incompatible with muzzle brakes. However, by then this had been disproved by the Soviet 100mm T12 towed anti-tank gun, which was fitted with a pepper-pot type of muzzle brake and fired APFSDS projectiles, and by the 90mm F4 gun mounted in some French light armoured vehicles which also fires APFSDS projectiles whilst fitted with a single-baffle muzzle brake.

The efficiency of the muzzle brakes η is defined in terms of the kinetic energies of the recoiling mass when it recoils freely as follows,

$\frac{RE_M}{RE_0}$ $1-\eta$

$$\eta = 1 - \frac{\text{recoil energy with muzzle brake}}{\text{recoil energy without muzzle brake}} \qquad 4.19$$

In consequence, the impulse I_M which acts on the gun with a muzzle brake is related to the firing impulse I which acts on the gun without a muzzle brake, and which is given by equation 4.17, and to the muzzle brake efficiency by the following equation:

$\left(\frac{I_M}{I_0}\right)^2$ $1-\eta$

$$I_M = I\sqrt{1-\eta} \qquad 4.20$$

The efficiency of muzzle brakes has been generally between 30 and 40 per cent but the muzzle brake developed by Bofors around 1980 for an experimental

Fig. 4.8 High-efficiency muzzle brake developed by Bofors to fire a 120mm tank gun from the relatively light UDES-XX-20 articulated vehicle. (Bofors)

version of the Rheinmetall 120mm smooth-bore gun has had an efficiency of 50 per cent. Guns intended for installation in very light vehicles have been fitted with muzzle brakes with even higher efficiencies. For example, the muzzle brake of the Cockerill 90mm Mk.7 gun has an efficiency of 55 per cent and that of the Mecar 90/47 gun has an efficiency of 70 per cent. Such high muzzle brake efficiencies reduce considerably the magnitude of the firing impulses and consequently also reduce the average recoil forces. But, as more propellent gases are deflected rearward, the resulting overpressure causes increasing discomfort to the crews of vehicles and the blast which goes with it creates dangers.

4.7 Automatic Loading Systems

Like other guns of their calibre, tank guns have been loaded manually but since the Second World War there has been a slowly growing interest in systems which would load them automatically. Development of automatic loading systems started during that conflict in Germany and in the United States, where one was actually built by 1945 for use with a 75mm gun in the T22E1 medium tank (4.17). Work on automatic loading systems continued in the United States during the late 1940s and throughout the 1950s but the next major step towards their use in tanks was taken in France with the development of the semi-automatic loading system for the 75mm gun of the AMX 13 light tank, the first prototype of which was completed in 1950.

Little further progress was then made until the development in Sweden of the turretless S-tank, which was originally built in 1961 and which became the first tank with a fully automatic loading system to go into service. An automatic loading system was also incorporated in the MBT-70 which was developed by the United States and Germany during the late 1960s, but which was not put into service. However, at about the same time another system was developed in the Soviet Union for the T-64 and T-72 tanks, which became during the 1970s the first turreted tanks to go into service with automatic loading. Even earlier an automatic loading system was incorporated in the Soviet BMP infantry armoured vehicle for its turret-mounted 73mm gun.

Other automatic loading systems developed between the late 1960s and the early 1980s in Britain, Germany, Sweden and the United States did not advance beyond test rigs or experimental vehicles. But they embodied new concepts and were for the first time applied to guns mounted externally, on pedestals or in unmanned, remotely controlled turrets. The first of the vehicles with a pedestal-mounted gun was the COMRES 75, which was built in Britain in 1968. It was followed by the construction during the 1970s of the VT-1s test vehicle with a pedestal-mounted gun in Germany and of an experimental vehicle in Sweden, also based on the German Marder infantry armoured vehicle. In 1980 the first vehicle with an unmanned, remotely controlled turret was built in the United States by the AAI Corporation. This was the Rapid Deployment Force Light Tank, which was based on the 75mm gun armed High Survivability Test Vehicle, Light Weight. In 1985 came the second experimental vehicle with an unmanned, remotely controlled turret, the Tank Test Bed, built by General Dynamics on an M1 tank chassis and armed with a 120mm smooth-bore gun.

One of the main advantages of automatic loading systems, which their developers sought to exploit from the start, has been a higher rate of fire than that possible with manual loading. Thus the original US system tried in the T22E1 medium tank provided a rate of fire of 20 rounds per minute and that incorporated in the

Fig. 4.9 Cartridge case ejected on firing from a Steyr SK-105 Kürassier with a turret bustle semi-automatic loading system. (Steyr-Daimler-Puch)

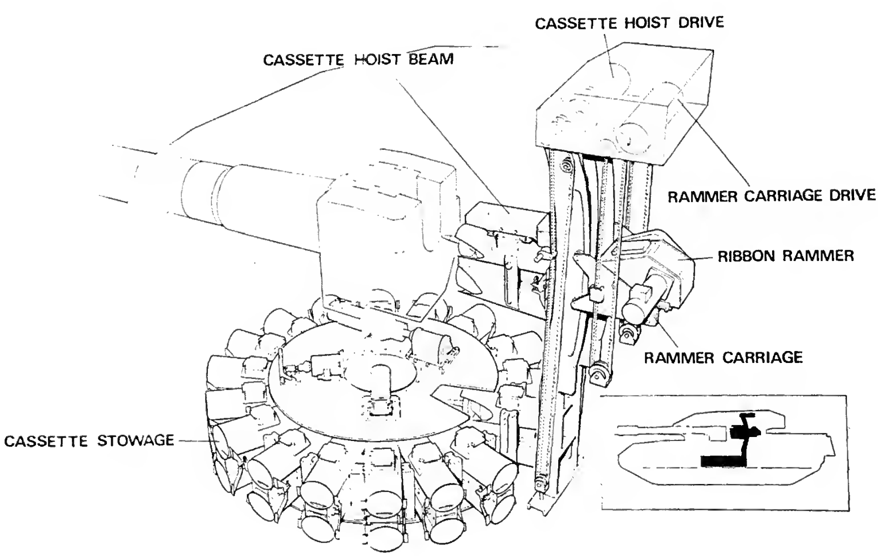


Fig. 4.10 Drawing of an experimental carousel-type auto-loader developed in Britain by Air-Log Ltd. (Air-Log)

Swedish S-tank enables its 105mm gun to be fired at the rate of 15 rounds per minute whereas the highest rate of fire that can be achieved with manually loaded guns of the same calibre is 8 to 10 rounds per minute.

As the rate of fire of automatically loaded guns is inversely related to their calibre, the highest rates of fire are achieved with the smaller calibre guns. For example, the 75mm XM274 gun mounted in the US HSTV-L and RDF/LT could be fired at the rate of 60 rounds per minute and the 57mm Bofors gun mounted in 1977 in Germany in the experimental *Begleitpanzer* had a rate of fire of 200 rounds per minute. On the other hand, the automatic loading system of the 120mm gun of the US Tank Test Bed was designed to provide a rate of fire of 12 rounds per minute. A much higher rate of fire of 70 to 80 rounds per minute had been achieved with a 120mm gun developed during the 1950s by Bofors but this was an anti-aircraft gun and as such was not subject to the same space and weight constraints as tank guns.

The second advantage of automatic loading systems is that they can handle heavy rounds which are difficult to load manually. This became important for the first time during the 1950s when guns of 120 or even 155mm firing full-calibre AP projectiles were being considered. The ability of automatic loading systems to handle heavy rounds then decreased in importance with the development of lighter ammunition with discarding sabot projectiles and combustible or semi-combustible cartridge cases and with no increase in calibre beyond 120mm. But it

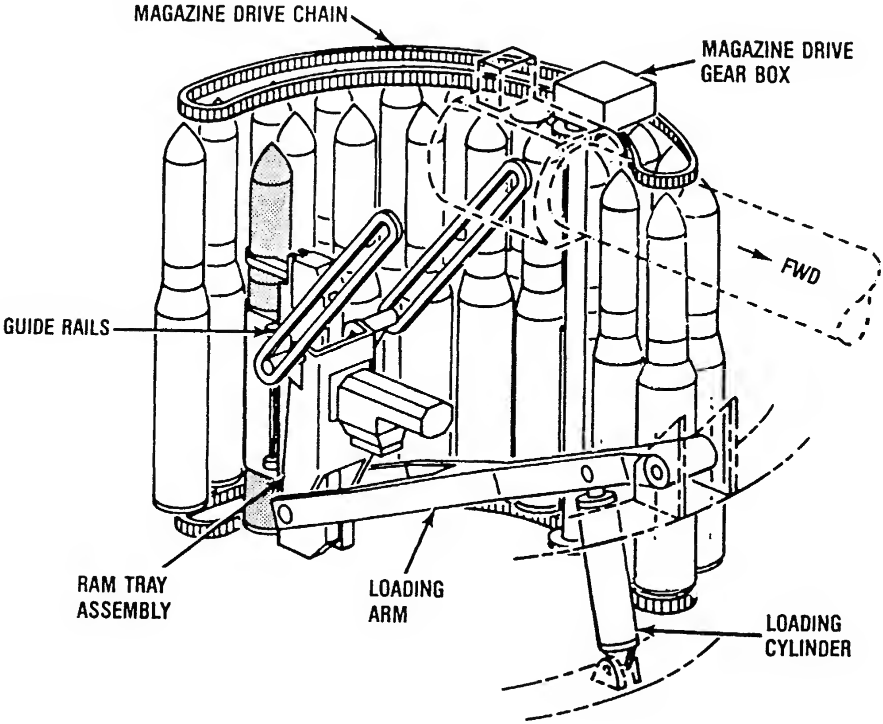


Fig. 4.11 Swinging arm auto-loader developed in the United States by FMC Corporation for the CCVL light tank. (FMC Corp)

will become important again if or when the calibre of tank guns increases further.

The third and much more recently recognised advantage of automatic loading systems is that they allow the armament to be remote from the crews of tanks. This extends the range of possible configurations of tanks to designs which present smaller targets to enemy weapons, particularly in hull-down positions, or which reduce the danger to the crew from ammunition fires.

Automatic loading systems also eliminate the need for a human loader and make it possible, therefore, to reduce the crew of a battle tank from four to three men, or even to two. In consequence, the internal volume of tanks and hence their size can be reduced, although it is more difficult to maintain and to operate a tank for a crew of three and even more of two men than for the customary crew of four.

The various automatic loading systems which have been devised can be divided into three categories according to the degree of freedom of movement between the gun mounting and the ammunition magazine. One category consists of systems where there is no freedom of movement or, in other words, where the gun mounting and the magazine are fixed in relation to each other. They are the simplest and have the shortest transit distance for the ammunition, which implies the possibility of a high rate of fire. But they are applicable only to tanks with particular configurations and their use imposes constraints in one or more respects. For instance, an automatic loading system of this kind is used in the S-tank, but only because the latter has a gun mounting fixed in its hull, which means that the gun can be elevated only by altering the pitch of the hull by means of an adjustable suspension and traversed only by turning the whole vehicle.

Another system in the same category is that of the AMX-13 light tank which has the ammunition magazine mounted in the bustle of a trunnion-mounted or oscillating turret and which, consequently, rotates in the vertical plane together with the gun and the upper part of the turret. However, oscillating turrets suffer from the disadvantage of being heavier than more conventional turrets because of the inevitable overlap between the armour of their two halves. They are also more difficult to seal and when they have a bustle they are higher and do not allow as much elevation as other turrets.

Yet another system in this category involves the attachment of an ammunition magazine to the cradle of a gun, which is mounted and elevated in the usual way. This is easily done with smaller calibre guns, such as the 57mm Bofors gun of the *Begleitpanzer*, but in the case of large calibre guns the capacity of the magazine is restricted to a few rounds because of the limited amount of space available within tank turrets.

The second category of automatic loading systems consists of those with one degree of freedom between the gun mounting and the ammunition magazine, that is systems in which the gun rotates in the vertical plane in relation to the magazine. In the simplest case, exemplified originally by the US-German MBT-70, the magazine is located in the turret bustle and to load it the gun is decoupled from its elevation drive in order to bring it in line with the loading chute of the magazine. This converts the system temporarily into one of the first category but after a round has been rammed into it the gun is rotated back into engagement with its elevation drive. In addition to being relatively simple, an automatic loading system with a magazine in the turret bustle allows almost complete separation of the ammunition from the crew. But it results in the ammunition being located relatively high in the tank where it is more likely to be hit. Nevertheless, systems of this

kind have been adopted during the 1980s for the French AMX Leclerc and the Japanese TK-X tanks.

In the other systems of the second category the ammunition is located within the turret basket, with the rounds stowed either in a horizontal position in a magazine on the floor of the basket or in a vertical position, in a circular row. In the first case the rounds can lie alongside each other, as in the original US system tried in the T22E1 tank, or are laid radially, as in the carousel type magazine of the Soviet T-72 tank. The latter enables more rounds to be stowed within the confines of the turret basket but precludes the use of conventional one-piece rounds because of their length. Instead, separated, two-piece ammunition has to be used, as in the T-72 where the carousel magazine is loaded with cassettes in which the propellant charge lies on top of the projectile and where, consequently, there has to be a two-stage process of ramming the projectile and the charge into the breech. In the second case the rounds are either nose up or nose down, to suit the kinematics of the loading mechanism, and are moved in their holders into alignment with the mechanism by roller chains. In the case of the carousel magazine this is done by rotating it.

The loading mechanism itself is based either on a swinging arm, pivoted about the gun trunnions, or on a hydraulically or electrically powered hoist, as in the Soviet T-72 and the BMP infantry vehicle, and in the US Tank Test Bed. With the swinging arm loader and with a hoist moving along a circular track centred on the gun trunnions the gun can be loaded at any elevation, provided there is enough room behind the breech for the rounds. But with fixed, one-piece ammunition this requires the gun trunnions to be well forward, ahead of the turret ring. Otherwise the gun has to be elevated to a fixed loading position and the path of the rounds from the magazine to the breech is more complicated.

Compared with other systems of the second category, those with an ammunition

Fig. 4.12 Scale model of the Swedish UDES-19 tank concept which embodies an auto-loader with a swinging arm rotating about the pedestal of an externally mounted gun and an external ammunition magazine.

magazine within or under the turret basket offer the advantage of the ammunition being located much lower, below the level of the turret ring instead of above it. However, they make the interior of the turret cramped and virtually rule out the possibility of separating the ammunition from the crew, unless the turret is unmanned and operated by remote control, as in the US Tank Test Bed.

The third category of loading systems involves two degrees of freedom between the gun mounting and the ammunition magazine, the latter being fixed in relation to the hull while the gun is free to rotate relative to it in elevation and in azimuth. One example of this is the system devised for the Swiss NKPz tank project of the late 1970s. In this the ammunition magazine was located at the rear of the hull and the rounds were fed from it, one at a time, under the turret basket where they were rotated into alignment in azimuth with the gun and from where they were then lifted up for loading into the breech by a swinging arm. Another example of a two-degree of freedom system has been provided by the Swedish UDES-19 tank concept. This involved the location of the ammunition in an external magazine behind the hull from which rounds were to be pushed, one at a time, into a loading tube attached to an arm that could rotate about the base of the pedestal of the externally mounted gun. The arm aligned the tube with the gun in azimuth and rotated in elevation about the base of the pedestal to lift the tube up to the breech for the loading of the round.

The system embodied in the UDES-19 concept resulted in a complete separation of the ammunition from the crew and therefore reduced the danger to the latter arising from ammunition fires. But it required remote operation of the gun and posed other problems associated with externally mounted guns. It also involved a relatively long loading path, almost all of which was outside the vehicle and therefore subject to various hazards. The latter problem did not exist with the system proposed for the NKPz in which the loading path was entirely within the vehicle but it was still relatively long as well as complex, which was bound to have an adverse effect on the rate of fire and reliability. Moreover, although the ammunition was to be located in the NKPz where it was least likely to be hit, and although all of it was immediatly available for the gun, which had been achieved previously only in the S-tank, it could not be separated completely from the crew because it had to move, albeit rapidly, through the crew compartment.

4.8 References

4.1 *Interior Ballistics of Guns*, AMCP 706-150, USA Army Materiel Command, Washington, 1965, Chapter 1.

4.2 *Handbook of Weaponry*, Rheinmetall, Düsseldorf, 1982, p.29.

4.3 *Handbook of Weaponry*, op.cit., p.93.

4.4 J J Rocchio, R W Deas and J M Frankle, 'High Performance Propelling Charge Design for the 105mm M68 Tank Gun,' *4th International Symposium on Ballistics*, Monterey, 1978.

4.5 K Ryf and E Bronnimann, 'A New Concept for High Performance Ammunition Propellants', *9th International Symposium on Ballistics*, Shrivenham, 1986.

4.6 G Bertrand, G Gallagher and J J Maroney, *A High Performance Experimental Smooth Bore Gun*, Technical Report 484/64, Canadian Armament Research and Development Establishment, Valcartier, 1964.

4.7 I W May, A F Barran and P G Baer, 'The Travelling Charge Concept Revisited,' *4th International Symposium on Ballistics*, Monterey, 1978.

4.8 M E Backman and W Goldsmith, 'The Mechanics of Penetration of Projectiles into Targets,' *International Journal of Engineering Science*, Vol.16, No.1, 1978,

pp.1-99.
4.9 V Hohler and A J Stilp, 'Penetration of Steel and High Density Rods in Semi-Infinite Steel Targets', *3rd International Symposium on Ballistics*, Karlsruhe, 1977.
4.10 A Tate, K E B Green, P G Chamberlain and R G Baker, 'Model Scale Experiments on Long Rod Penetration,' *4th International Symposium on Ballistics*, Monterey, 1978.
4.11 G Birkhoff, D P MacDougall, E M Pugh and G I Taylor, 'Explosives with Lined Cavities,' *Journal of Applied Physics*, Vol.19, June 1948.
4.12 E M Pugh, R J Eichelberger and N Rostaker, 'Theory of Jet Formation by Charges with Lined Conical Cavities,' *Journal of Applied Physics*, Vol.23, No.5, 1952.
4.13 F E Allison and R Vitalli, *A New Method of Computing Penetration Variables for Shaped Charge Jets*, BRL Report No.1184, Aberdeen Proving Ground, 1963.
4.14 P C Chou, E Hirsch and W Walters, 'The Virtual Origin Approximation of Shaped Charge Jets,' *6th International Symposium on Ballistics*, Orlando, 1981.
4.15 M Held, 'Evaluation of Shaped Charge Penetration Efficiency by Advanced Diagnostic Techniques,' *6th International Symposium on Ballistics*, Orlando, 1981.
4.16 *Handbook on Weaponry*, op.cit., p.430.
4.17 *A History of Automatic Loading Equipment*, Report No.RR-13, Ordnance Tank-Automotive Command, Center Line, Michigan, April 1960.

4.9 Selected Bibliography

(Excluding works already listed under References)

Elements of Armament Engineering, Part One, Sources of Energy, AMCP 706-106, US Army Materiel Command, Washington, August 1964.

Elements of Armament Engineering, Part Two, Ballistics, AMCP 706-107, US Army Materiel Command, Washington, September 1963.

Interior Ballistics of Guns, AMCP 706-150, US Army Materiel Command, Washington, February 1965.

Oerlikon Pocket-Book, Oerlikon-Bührle, Zurich, 1981.

W E Baker, P S Westine and F T Dodge, *Similarity Methods in Engineering Dynamics*, Hayden, Rochelle Park, 1973.

J Corner, *Theory of the Interior Ballistcs of Guns*, Wiley, New York, 1950.

D K Davison and B K Arvidsson, 'Optimization of a 90mm Shaped Charge Warhead,' *2nd Symposium on Interaction of Non-Nuclear Munitions with Structures*, Panama City Beach, Florida, 1985.

R DiPersio, J Simon and A B Meredino, *Penetration of Shaped Charge Jets into Metallic Targets*, BRL Report No.1296, Aberdeen Proving Ground, 1965.

E Drosen, 'Das Automatische Laden der Panzerkanone,' *Soldat und Technik*, No.10, 1983.

D L Hall, 'Scaling Laws for Predicting Ballistic Limits for Rod Type K.E. Penetrators,' *5th International Symposium on Ballistics*, Toulouse, 1980.

J T Harrison, BASC, 'An Analytical Code for Calculating Shaped Charge Properties,' *6th International Symposium on Ballistics*, Orlando, 1981.

F R W Hunt, *Internal Ballistics*, HMSO, London, 1951.

P W Krapke, 'Upgrading by Automatic Loading,' *Armada International*, Vol.8, No.4, July-August, 1984.

H Krier and M Summerfield, eds., *Interior Ballistics of Guns*, American Institute of Aeronautics and Astronautics, New York, 1979.

J S Rinehart and J Pearson, *Behaviour of Metals under Impulsive Loads*, Dover, New York, 1954.

L Stiefel, ed., *Gun Propulsion Technology*, American Institute of Aeronautics and Astronautics, Washington, 1988.

J A Zukas, T Nicholas, H F Swift, L B Greszczuk and D R Curran, *Impact Dynamics*, Wiley, New York, 1982.

Chapter 5

Vision and Sighting Devices

5.1 Target Acquisition

The effective use of tanks' armament depends on the ability of their crews to acquire and then to engage targets with a high probability of hitting them in a minimum of time.

The acquisition of targets is generally considered to involve three successive events. The first is that of detection, or of becoming aware of the presence of a potential target. The second is that of recognition, or of seeing that the detected target is of a particular kind, such as a tank or a truck. The third event is that of identification, which is establishing, for example, that the target is not only a tank but a particular type of tank.

Identification is particularly important when there is a need to determine whether the target which is being acquired represents friend or foe. However, in many cases targets detected and recognised in a particular area or direction may be taken immediately to be enemy targets and the process of target acquisition need not proceed any further.

In its simplest form target acquisition amounts to the crews of tanks looking out of open hatches and searching for and locating targets with or without the aid of binoculars. Target acquisition from under armour implies the performance of similar functions but with the aid of built-in vision devices. To suit their purpose the latter need to incorporate low power but wide field of view optics for surveillance and target detection. However, unless the targets are at short range, their recognition, identification and even detection require high power optics which must, therefore, be provided also.

5.2 Unit Power Devices

Vision devices developed for target acquisition have taken several different forms. Most of them have been designed principally for use by tank commanders, who are generally assigned the primary responsibility for target acquisition.

An early and simple form of day vision devices have been unit power periscopes mounted in the roofs of turrets above the commander's stations and rotatable in azimuth. Vickers periscopes of this kind were installed in British tanks from the A.9 of 1934 to the Crusader of 1942. By being rotatable such periscopes could be used for surveillance and target searching over a fairly wide arc but, like other single periscopes, they cut off severely the edges of their users' field of view and thus prevented them from taking advantage of peripheral vision. Moreover, while

their unit power made them effective for detecting targets at short range it also made them relatively ineffective at long ranges.

The early US M4 medium tanks also had a rotatable periscope but mounted in the cover of the commander's hatch which could be rotated itself (5.1). This may have facilitated its use in some cases but once a periscope was mounted in a rotatable cover there was little point in it being rotatable itself. This was recognised, among others, in the design of the British Centaur and Cromwell tanks which had a unit power periscope fixed in the front and another in the back, facing rearwards, of a rotating circular cover that formed part of a rudimentary commander's cupola. Rotation of the cover provided all-round vision but inevitably required time for scanning and the use of a single periscope failed again to make use of peripheral vision.

To search more quickly over a wide arc and to make use of peripheral vision it is clearly necessary to install more than one periscope. In fact, the Comet tank, which came after the Cromwell, was fitted with eight periscopes in its rotating cupola cover, and so was the contemporary Churchill VII tank. But once so many periscopes are used they form a ring which provides almost complete all-round vision and there is little to be gained by rotating them. They are, therefore, used more effectively in the form of a fixed ring, which is simpler to install, is lighter and requires a smaller opening in the turret roof and, therefore, weakens the latter less.

A fixed ring of periscopes appears to have been used for the first time in the

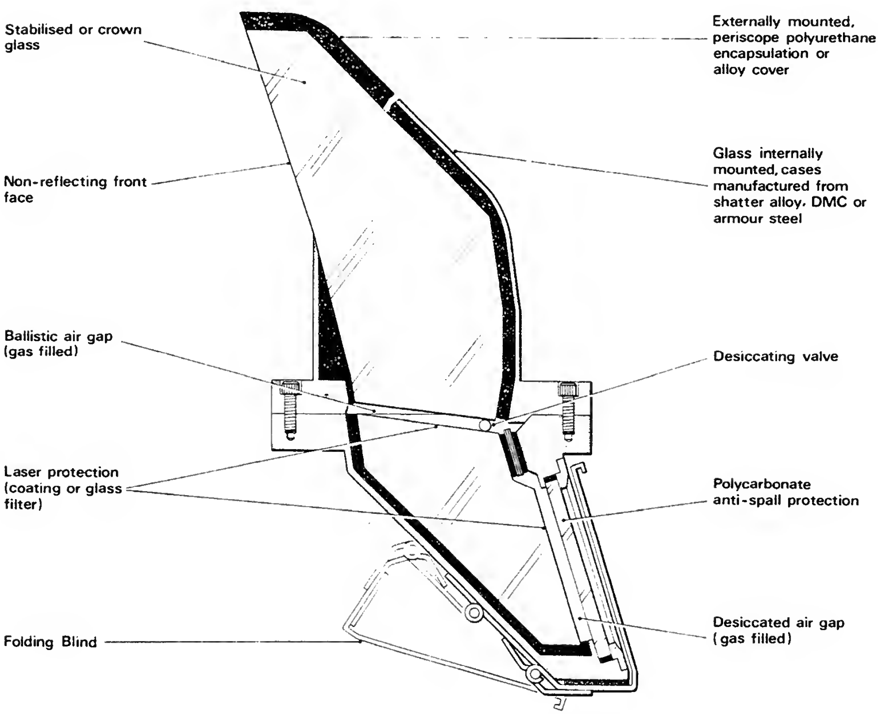


Fig. 5.1 Helio unit power periscope with a forward inclined front face to reduce reflections. (Helio Mirror)

German Pz.Kpfw.II light tank, which was provided with eight of them in 1940, after the early campaigns of the Second World War when its commanders complained about the limited vision provided by its original vision devices (5.2). However, the fixed ring of periscopes did not gain prominence until it was adopted two or three years later in the German Panther and Tiger II tanks. Each of these tanks had a commander's cupola with a fixed ring of seven periscopes, which represented the most effective solution that had been devised for tank commanders until then.

The example set by the Panther and Tiger II was followed in the late 1940s by the French AMX-13, which has had a commander's cupola similar to theirs with eight periscopes, and fixed rings of periscopes have been adopted since in several other tanks.

On the other hand, US tanks continued to have rotatable commander's cupolas with a ring of six vision blocks and a rotatable periscope in the hinged cupola cover. Cupolas of this type were first developed in 1942 for the improved version of M4 medium tanks and they were subsequently used not only on the M26 and M46 but also on the T42 medium tanks. The vision blocks of laminated glass are simpler than periscopes, of course, and offer somewhat better resolution and larger fields of view. But, even if they are inclined, as they have been in the cupolas of the US tanks, they do not allow the head of the viewer to be much below their level and, therefore, below that of the turret or hull roofs. In contrast, periscopes allow the head of the viewer to be well below the level of their objective glasses and, in consequence, to be protected by the main turret or hull armour and not merely by that of the cupola.

The disadvantages of vision blocks were acknowledged in the design of the US M48 medium tank, which in its original form had a low, rotatable commander's cupola with a semi-circle of three forward facing periscopes and a fourth periscope facing to the rear. But vision blocks were reintroduced on the M48A1 with the adoption of the dual-purpose M1 commander's cupola, which was designed not only to meet the commander's vision requirements but also to satisfy the peculiar importance attached by the US Army to the use of 12.7mm machine guns by tank commanders. The consequent installation of this weapon in the M1 cupola not only made it large but placed the commander's head even higher in relation to the turret roof than the vision blocks would have done by themselves and, therefore, made him still more vulnerable to hits by major calibre projectiles. The M1 cupola also made the silhouette of the tank higher and the machine gun installed in it diverted the commander's attention from his other and much more important responsibilities, including the acquisition of targets for the main armament of the tank.

Nevertheless, cupolas with internally mounted 12.7mm machine guns were fitted not only on most M48 but also on M60 tanks, including the M60A2, whose cupola was almost grotesquely high. However, cupolas of this kind and vision blocks were no longer used on the US-German MBT-70 and they are not used on the US M1 tank, which has a ring of six unit power periscopes mounted in a very low, rotating commander's cupola.

Unit power periscopes similar to those adopted for the commanders have also been provided for the drivers of tanks and have been installed for the use of gunners and loaders as additional means of observation. Most of them have been fixed but some of those provided for the drivers and loaders have been tiltable and even rotatable in azimuth.

The construction of the periscopes has varied. Some, like the Vickers periscopes used in the past in British tanks, consist in essence of two glass prisms separated

by an appropriate distance and contained within a box-like structure. Others, used more recently in US tanks, consist of two mirrors set at 45° and separated by a block of an acrylic thermoplastic to which they are actually cemented. Periscopes with plastic elements are relatively light but the latter tend to deteriorate or craze with age and glass prisms are preferable optically. If two separate glass prisms are used they are also safer than monobloc prisms of plastic or glass, because they reduce the risk of damage to the upper part of the periscope being propagated to its lower part and causing injury to its user. However, the space between the two prisms needs to be filled with nitrogen and sealed. The most recent type of unit power periscope, developed in Britain by the Helio Mirror Company and first used in Chieftain tanks, has a forward sloping upper face or window in order to reduce the risk of it reflecting sunlight or the beam of a searchlight and thus revealing the position of the tank.

Typical periscopes have a horizontal field of view ranging from 56° of the M223 used in the AMX-30 to 74° of the No.7 Mk.1 used in the Centurion tank, the corresponding vertical fields of view being 10° and 25.5°. However, the No.36 Mk.1 driver's periscope developed by Helio Mirror for the Chieftain tank has a horizontal field of view of 106°, which is almost equal to that provided by two of the more conventional periscopes. In consequence, a single periscope of this type has been considered adequate for the driver. But it is doubtful if it represents a solution as good as that provided by three more conventional driver's periscopes installed, for instance, in the AMX-30 and Leopard 1 which have a greater total field of view and are less likely to be all damaged on any one occasion by enemy fire.

An even greater horizontal field of view of 140° has been achieved with the No.40 Mk.2 periscope, nine of which are mounted in the commander's cupola of the Chieftain to give good, all-round vision. Inevitably, such a large horizontal field of view requires the periscope to be wide and the width of the No.40 Mk.2 periscope is, in fact, 317.5mm, which is more than twice that of the periscopes fitted in the Leopard 1, that have a 67° field of view. A ring of such wide periscopes is therefore large and their windows present large and vulnerable areas of glass.

It should be noted that the fields of view quoted above are those for a fixed position of the eye and not the 'dynamic', or 'total', fields of view which are occasionally given and which are considerably larger but somewhat less realistic.

5.3 High Power Periscopes in Rotatable Cupolas

Although rings of unit power periscopes have come to be accepted as the best vision devices for surveillance and for target acquisition at short ranges they do not provide the magnification required for target acquisition at long ranges. They need to be supplemented therefore by additional, high power sights.

The need for such sights has grown with the increasing power of tank guns, which has made it possible to engage targets at progressively longer ranges. In particular, as tanks came to engage other tanks at up to 2000 m, as they did towards the end of the Second World War, unit power devices became inconsistent with the capabilities of tank guns and to match them tank commanders had to be provided with additional, high power instruments.

In fact, rotatable cupolas with a combination of high power and unit power periscopes were used even before the Second World War, on the APX 4 turrets of the French Char B and Somua S-35 tanks. The cupolas differed from those

mounted later on other tanks in having the shape of small, solid domes and they incorporated a x4 binocular and two unit power periscopes (5.3). In principle the vision devices which they contained were well in advance of those provided for the commanders of other tanks. However, their effectiveness was reduced because the commanders of the Char B and S-35 had to operate the turrets of the two tanks by themselves and were, therefore, occupied with other tasks when they might have made more use of the vision devices provided for them.

Rotatable cupolas with high as well as unit power periscopes were reintroduced after the Second World War when in the late 1940s British Centurion tanks were provided with a commander's cupola with a rotating ring mounting not only nine unit power periscopes but also a binocular periscope with x10 magnification. One of the nine unit power periscopes was then replaced by a monocular periscope sight with x7 magnification with which the commander could aim at a target and then have the gunner traverse the turret to align his sight with the commander's, this being accomplished with the aid of a simple blade vane mounted on the turret roof in front of the cupola. The binocular periscope and the separate sight were then replaced by a single commander's sight, which could be used for both target acquisition and for laying the main armament on target. The latter involved the use of a graticule image projector, or collimator, located on the underside of the cupola and linked to the gunner's sight which injected the gunner's sight graticule pattern into the commander's sight when the two sights were in optical alignment. The cupola with all its optical instruments was normally rotated relative to the turret by hand-driven traverse gears but an automatic contra-rotating gear was also incorporated to help bring the main armament more quickly on to the target which the commander had selected. Its function was to maintain the cupola's bearing relative to the hull while the turret was being swung round to align the sights. The great advantage of this arrangement has been that the commander can designate targets much more rapidly to the gunner, or to engage them himself, if necessary.

The equipment described above was fitted in the final, Mark 13 version of the Centurion and was very similar to that subsequently adopted for the Chieftain. The latter incorporates a commander's sight with a unit power channel and a binocular periscope with x10 magnification in the Mark 2 and x15 magnification in the Mark 5 versions. There are also the nine unit power periscopes mentioned earlier but they form a ring which does not rotate in relation to the turret. The principal advantage of this arrangement over that of the Centurion is a reduction in the mass of the cupola which has to be rotated to scan with the commander's sight independently of the turret.

An arrangement of vision devices similar in principle to that of the Chieftain has also been adopted for the French AMX-30, which has a cupola with a fixed ring of ten unit power periscopes giving very good all-round vision and a rotatable cover mounting a x10 binocular periscope. As in the Chieftain, a contra-rotation system enables the commander to slew the turret to align the main armament with his binocular periscope without losing sight of the target. But, in contrast to the Chieftain, there is no provision in the cupola for aiming the main armament, which the commander of the AMX-30 can only do by resorting to the optical rangefinder-cum-sight mounted across the turret ahead of the cupola.

A somewhat simpler solution, resembling that used in the early Centurions, was adopted in the Soviet T-54, T-55 and T-62 tanks. It is exemplified by the commander's equipment in the T-54 which consists of a commendably low, rotatable cupola with a TPK-1 periscope with x5.5 magnification and four unit power periscopes. As in other cases, rotation of the cupola enables the commander

to scan with his high power periscope independently of the turret traverse and a line-up switch makes it possible for him to slew the turret, to align the main armament with his periscope, when he has acquired a target.

The Swedish S-tank also has a low, rotatable cupola with one high power and four unit power periscopes. But it is of a much more advanced design than the cupolas of the Soviet tanks mentioned above and, so far as its high power OPS-1 periscope is concerned, it is also superior to the other commander's cupolas. The OPS-1 periscope, developed by the Jungner Company, is a binocular instrument with three magnifications of x6, x10 or x18 and a unit power channel which, when used, provides a wide horizontal field of view of 102°. The left eye piece of the periscope has line-up indicators showing the traverse or elevation required to align the periscope with the main armament, or vice versa, for target engagement or for designating the target to the gunner, and while the hull with the armament is being traversed the cupola can be counter-rotated automatically to help the commander retain the target in his field of view.

5.4 Panoramic Periscopes

The different rotatable cupolas mounting high power periscopes and linked with the main armament represent a major advance in observation and target acquisition on earlier equipment but they are not without their disadvantages. The principal one is their size and the mass which has to be rotated, even when the indispensable unit power periscopes are not part of the rotating assembly. These disadvantages favour the alternative method of using high power optics in the form of periscopes rotatable in azimuth by themselves or of fixed periscopes with rotatable heads.

The first solution appears to have been adopted in only one recently built tank, in spite of the extensive use of rotatable unit power periscopes. The tank is the Scorpion, built in Britain by the Alvis Company, which has a rotatable commander's binocular periscope with a magnification of x10. The high power periscope takes the place of the forward facing of the unit power periscopes, of which there is still a ring of seven, and its rotation is limited, resulting in a total horizontal field of view of approximately 85°.

The use of fixed periscopes with a rotatable head, or in other words of panoramic periscopes offers all round 360° vision and a better solution from the ergonomics point of view because the user does not have to move his head to follow the rotation of the periscope. However, the lack of a physical relationship between the position of the head of the periscope and that of the user's head can cause orientation problems.

Panoramic periscopes antedate the appearance of tanks, their development having been pioneered in Germany by the Goerz Company well before the First World War (5.4). They were developed originally for sighting artillery guns but although they were widely adopted for that purpose from their inception their adoption for tanks has been much slower. They were used for the first time in tanks in 1929-1930, when they were fitted in the *Leicht-* and *Grosstraktoren*, the experimental tanks built at the time in Germany and subsequently tested in the Soviet Union at Kazan (5.5). The periscopes were the TRF-3, or *Turm-Rundblickfernrohr 3* made by Zeiss, which had a head that could be rotated through 360° for all-round observation. The top prism contained in the head could also be tilted and, when the head was locked in azimuth, it was moved in elevation by a linkage connected to the gun mounting, so that the periscope could be used

for aiming the tank's gun and it provided a magnification of x2.5.

A very similar Zeiss panoramic periscope was fitted in the Strv m/31 tank built in Sweden in 1934 by the Landsverk company. Similar periscopes, based probably on the Zeiss model, also appeared in 1935 on Soviet BT-5 tanks and later also on other Soviet vehicles. In particular, the T-34 and KV tanks, which were introduced in 1940, were both fitted with commander's panoramic periscopes. Thus, the commander of the T-34, who also acted as its gunner, was provided with the PT-47 periscope, which was the same in principle as the Zeiss TRF-3. The KV commander's PTK periscope was virtually the same as the PT-47 and like the Zeiss model had a magnification of x2.5.

However, the use of panoramic commander's periscopes in Soviet tanks was abandoned during the Second World War in favour of other solutions which were optically more primitive. In particular, the T-34-85, which became the principal Soviet tank after 1943, was provided with a cylindrical commander's cupola with five vision slits protected by glass blocks.

The use of panoramic commander's periscopes was not revived until the late 1950s when the TRP-2A periscope was adopted in Germany for the Leopard 1 tank. The periscope was made by Steinheil-Lear-Siegler and has zoom optics giving a magnification varying continuously from x6 to x20 (5.6). It has been mounted in front of the commander's fixed and commendably low ring of eight

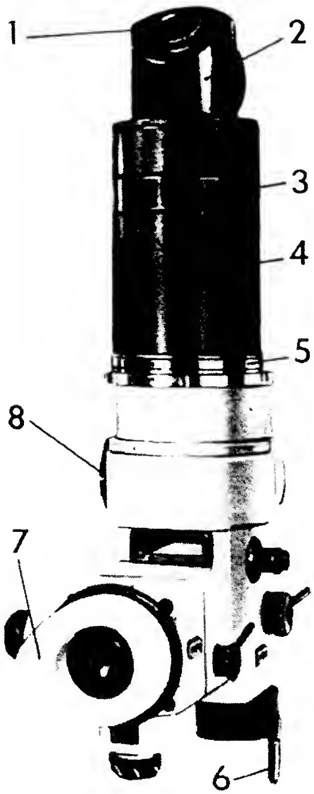


Fig. 5.2 Panoramic periscope with magnification varying from ×6 to ×20 mounted in the German Leopard 1 tank.
1 Dessicator cartridge
2 Rotating head
3 Sealing collar
4 Objective tube
5 Bayonet mounting ring
6 Hand crank for head drive
7 Eye guard
8 Ranging knob

unit power periscopes. Its rotatable head is linked to the turret traverse, so that the commander can use it not only for all-round observation independently of the turret position but also to align the gun with it. To do this he overrides the gunner's controls and traverses the turret, while the periscope automatically counter-rotates, so that the target stays in his field of view. An electrical system also feeds the periscope with gun elevation data, so that the commander can not only designate targets more quickly to the gunner but can also engage them by himself, if necessary.

The TRP-2A represents a major advance on the earlier panoramic periscopes. It does so as an optical instrument, being of the pancratic type. In other words, it offers the user a choice of different magnifications, instead of the single magnification of the earlier types, and the magnification varying not in one or two steps but continuously. The TRP-2A also represents a considerable advance from the gun laying point of view on the earlier periscopes, the heads of which could only be rotated manually or locked mechanically to the gun. Moreover, TRP-2A is used in conjunction with a ring of unit power periscopes while the earlier panoramic periscopes were used by themselves, which perforce failed to provide adequate vision. This fact was clearly demonstrated by the experience with the German Pz.Kpfw.II, which was provided originally with a commander's panoramic periscope but which was then fitted instead with a ring of unit power periscopes as a result of the complaints about vision mentioned earlier.

Nevertheless, the use of TRP-2A has been questioned on the grounds that the users of panoramic periscopes can become disoriented, although no significant orientation problems appear to have occurred with the 6500 Leopard 1s used by ten different armies. In principle, TRP-2A and all other panoramic periscopes are also open to the criticism that they are monocular instruments and therefore do not provide stereoscopic viewing. This implies a loss of the perception of depth, which can reduce the ability to detect targets in some circumstances. What is more, monocular instruments do not allow in general a fully relaxed use of both eyes, which produces minimum eye strain. This is of particular importance with optical instruments like the commander's periscopes, which are used for observing over relatively long periods of time, although it can be overcome to a large extent by the use of biocular eyepieces.

In practice the disadvantages of panoramic periscopes have been outweighed by their advantages and their use has spread since the 1950s. In fact, the example of Leopard 1 has been followed directly by the Israeli Merkava whose commander is provided with a panoramic periscope very similar to TRP-2A in addition to five fixed unit power periscopes.

A further development of the panoramic periscope was introduced in the late 1960s on the US-German MBT-70. The KRF periscope developed for it by Steinheil-Lear-Siegler incorporated for the first time a head prism which was stabilised about two axes for better observation on the move. Another development followed in the all-US version of MBT-70, the XM-803, which was fitted with a panoramic commander's periscope designed by Delco Electronics. This could be used not only for observation in daylight but also at night, by incorporating an image intensifier. Like the KRF periscope it also had a stabilised head prism, but instead of a magnification varying continuously from x4.5 to x15 it provided a choice of two, x3 or x8, magnifications for daylight viewing.

Zoom optics were also abandoned in two more recent Zeiss periscopes. One of them is the PERI R-12, which has been installed in the final, A4 version of Leopard 1. The other is the PERI R-17, which is installed in Leopard 2. Both

provide a stabilised line of sight and a magnification of x2 or x8 for day viewing. The PERI R-12 also incorporates an image intensifier for night viewing, which the PERI R-17 does not do because the commander of the Leopard 2 has a monitor connected to the thermal imaging system in the gunner's sight.

Similar developments have followed in France. The first panoramic commander's periscope to be adopted was the M 389 installed in the AMX-10 RC reconnaissance vehicle. It provides a magnification of x2 or x8 but is not stabilised and has no night viewing capability. On the other hand it can be used not only for observation and target acquisition but also for aiming the turret weapons and it can be counter-rotated while the turret is being traversed. But the somewhat later M 527 panoramic periscope mounted in the AMX-32 and AMX-40 prototypes has a stabilised line of sight and incorporates an image intensifier for night viewing as well as having a magnification of x2 or x8.

Both periscopes have been developed by the AMX-APX establishment of GIAT but the M 389 has been produced by the Societé d'Applications Generales d'Electricité et de Mecanique, or SAGEM, while the M 527 has been produced in collaboration with SERE-Bézu. The latter forms part of the Societé de Fabrication d'Instruments de Mesure, or SFIM, which has produced a series of gyro-stabilised sights for helicopters, starting with the pioneer APX Bézu M 260, and from the basis of its experience with them developed the VS 580 panoramic periscope for tanks.

The VS 580 periscope has a two-axis stabilised head mirror and a dual magnification of x3 or x10 for day viewing. It can also be fitted with an image intensifier for night viewing and with a laser rangefinder. Like the M 527, the VS 580 has

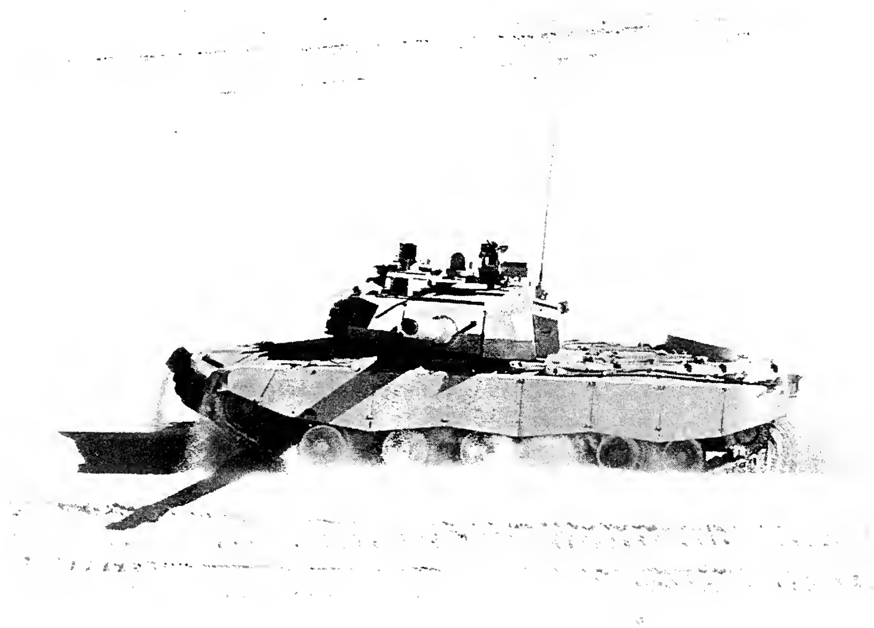


Fig. 5.3 Engesa Osorio with three independently stabilised sights for the gunner, commander and the thermal imaging system. (Engesa)

electronic controls incorporating logic circuits which allow the commander to align the gunner's line of sight with his own to designate targets to the gunner, or to fire the main armament himself. Alternatively, the commander can reverse the process and automatically align the periscope with the gunner's sight to monitor target engagement, or with any of his fixed unit power periscopes through which he may have detected a potential target. The attractive characteristics of the VS 580 periscope led to its adoption in the OF 40 tank produced by OTO-Melara and its installation in the Vickers Valiant prototype of the early 1980s. It was then also adopted for the South Korean Type 88 and for the more sophisticated version of the Engesa Osorio. In consequence, it became one of the first three stabilised panoramic periscopes to go into service in tanks, the other two being the Zeiss PERI R-12 and R-17.

The advantage of panoramic periscopes with gyro-stabilised head prisms or mirrors is that they decouple to a very large extent the line of sight from the motion of the vehicle and thereby increase the ability of tank commanders to detect targets when their tanks are moving off the roads. Stabilisation can also be applied, of course, to periscopes mounted in rotatable commander's cupolas. This has been done in fact with the OPS-1 periscope of the S-tank, which has a head prism stabilised in elevation and which is mounted in a cupola stabilised in azimuth. However, the inertia of a cupola is considerably greater than that of a head prism or mirror, which makes it difficult to stabilise the line of sight to the same degree of accuracy if this involves the stabilisation of the cupola. But the effect of the inertia of the cupola is confined to the stabilisation in azimuth which is less critical than stabilisation in elevation.

How accurately the line of sight can be stabilised was demonstrated by the periscopic sight with a head prism independently stabilised about two axes which was developed by Delco Electronics for the US XM-803. In particular, when this tank was driven cross-country at speeds of up to 30 km/h the standard deviation of the line of sight errors did not exceed 0.05 mil either in elevation or in azimuth (5.7). Similarly small stabilisation errors have been achieved with other panoramic periscopes such as SFIM's VS 580, with which the standard deviation is generally less than 0.1 mil. With some others it is 0.25 mil, which may be acceptable when they are used only for general observation but which is undesirably high for gun laying.

5.5 Fixed Commander's Sights

A far simpler although less effective way of complementing commander's low power vision devices with high power sights is to mount a fixed periscope in the turret roof ahead of the commander's station. This makes it easy to link the periscope with the main armament and the periscope can be simply a duplicate of the gunner's sight, which has been the case with a number of light armoured vehicle turrets. An example of them is the KUKA Type E4 two-man turret developed by Keller & Knappich Augsburg for the German Luchs reconnaissance vehicle, which has two Leitz PERI Z-11 sights. These are fixed periscopes with a tilting head mirror mechanically linked in elevation with the gun mounting and they provide x2 or x6 magnification as well as a separate unit power channel.

The relative ease with which a fixed periscopic sight can be linked with the main armament leads not only to the commander being able to fire it without the use of complicated controls but also to the stabilisation of his line of sight, if the vehicle is provided with stabilised gun controls and the sight has a pivoting top mirror.

However, because the sight mirror is then slaved to the main armament, the line of sight can not be stabilised to the high degree of accuracy possible with independently stabilised mirrors of panoramic sights. In fact, the standard deviation of the line of sight errors is at least two or three times as large when the sight is slaved to the gun as it is when it is independently stabilised. In consequence the commander's ability to detect targets on the move in degraded when his sight is slaved to the main armament.

What is more, the arc over which the commander can scan without traversing the turret is restricted to the field of view set by the size of the periscope and its magnification. At best this can only be similar to the field of view provided by the Jungner OPS-1 periscope mentioned earlier and in most cases it is likely to be considerably less. Thus the unit power window of a typical gunner's periscopic sight has a field of view of about 30° and its x8 magnification system of only 8°.

In view of this, commanders' high power sights which are fixed in azimuth are inadequate for battle tanks, although they are accepted for light armoured vehicles, mainly for cost reasons. Nevertheless, fixed commander's sights have been used in some battle tanks. One recent example of this is the simpler of the two versions of the Engesa Osorio which has two very similar, fixed OIP sights, the LRS-5 for the gunner and the SCS-5 for the commander. An earlier example is provided by the US M47 tank in which the commander has an M20 periscopic sight fixed in azimuth. A similar situation has existed in principle with the US M48 tanks where the only high power optics available to the commander have been those incorporated in the optical rangefinder fixed across the turret.

A somewhat similar situation also exists in the US M1 tank in which, apart from six unit power periscopes and a machine gun sight with x3 magnification, the commander is only provided with an optical relay from the gunner's primary sight. The latter gives him x10 as well as x3 magnification and, together with appropriate controls, ensures that he can engage targets as well as the gunner. But the arrangement adopted in the M1 restricts severely the ability of the commander to acquire targets independently of the gunner, which reduces the overall target acquisition capability of the tank, particularly when targets are scattered over a wide arc.

The provision for the commander of the M1 of little more than an optical relay from the gunner's sight implies that the gunner has to assume primary responsibility for target acquisition, unless the commander takes over his functions. The latter is clearly contrary to an efficient division of duties between the two crew members while the former takes away from the commander much of the responsibility for the vital task of acquiring targets and thereby prevents him from exercising full and effective control of the tank. The only way of rectifying this is to provide the commander with a high power instrument which is at least as good as the gunner's and independent of it as well as of turret traverse.

Such rotatable, high power instruments are essential for the effective acquisition of targets by the commander and they are also needed for surveillance over anything other than narrow arcs, as it is inefficient to scan by traversing the large turret of a battle tank and because the rotation of its turret can also reveal its position.

5.6 Gunner's Sights

Once a target has been acquired and is to be engaged, the tank's armament has to be aimed at it. This generally involves the use of a gunner's sight, of which there have been several different forms. The simplest and oldest is a straight-through

telescope with a graticule, or reticle, which provides one or a series of aiming marks. In the latter case the graticule takes the form of one or more range scales, each of which represents a series of aiming marks appropriate to one particular type of ammunition fired from the gun to which the telescope is attached. Given such a graticule, the gunner can immediately lay the gun with the elevation required to account for the action of gravity on the projectile by selecting the aiming mark appropriate to the ammunition being fired and the range of the target, assuming of course that he knows what the range is.

Apart from its basic simplicity, the straight-through telescopic sight has the great advantage of being rigidly attached to the gun mounting, which eliminates the possibility of alignment errors that exists whenever there is relative motion between the sight and the gun. However, the straight-through telescopic sight is awkward to use because the eyepiece has to be at a considerable distance from its pivot, which is on the axis of the gun trunnions, and therefore moves up and down over a relatively large arc as the gun is elevated or depressed. In spite of this, straight-through telescopic sights were used in many tanks up to the early 1940s and in particular in those built in Britain, including the Comet of 1944.

Some of the early telescopic sights such as that mounted in the Renault FT and the Aldis No.22 telescope of the Vickers Medium Mark I provided no magnification, which reflected the short range of engagement of the contemporary tanks. However, later telescopes provided magnification which increased steadily with the effective range of tank guns. Thus, the No.57 telescopic sight of the Comet had a magnification of x3 and the much earlier French Char B and S-35 already had x4 magnification.

In the mid-1930s the original, straight-through telescopes began to be replaced by articulated telescopic sights. With this type of sight the objective is still attached to the gun mounting, but there is an optical hinge behind it which enables the rear portion of the telescope and in particular the eyepiece to the fixed to the turret roof (5.8). As a result, the gunner does not have to move his head up and down when the gun is elevated or depressed, as he has to do with a simple telescopic sight. At the same time the articulated telescope retains the advantage of the objective remaining fixed to the gun and, hence, of being free of alignment errors.

Articulated telescopic sights appear to have been developed originally in Germany by the Ernst Leitz company. The first Leitz sight of this type was probably the TZF 4, which was produced for the 1935-designed Pz.Kpfw.II. At about the same time articulated telescopic sights also began to be fitted in Soviet tanks, the first of them being probably the BT-7. The TMFD sight of this type with a magnification of x2.5 was adopted for both the KV heavy and T-34 medium tanks, first built in 1939 and 1940, respectively. Other articulated telescopic sights have been used in all Soviet battle tanks built since then until the introduction of the

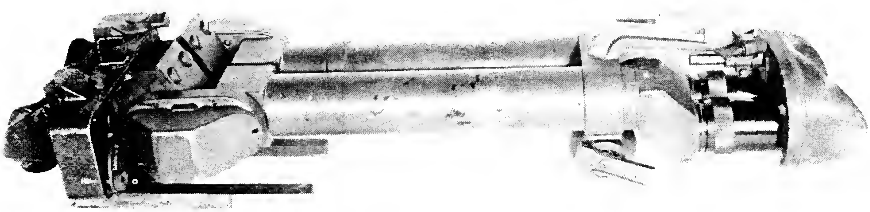


Fig. 5.4 Articulated telescopic gunner's sight of the German Tiger I heavy tank.

T-64 and T-72.

Concurrently with its adoption in Soviet tanks of the late 1930s, the articulated type of telescopic sight was also adopted in the Italian M13/40 and in the German Pz.Kpfw.III and IV. The TZF 5 telescopic sights of the two German tanks were produced by Leitz but they had the same x2.5 magnification as the Zeiss periscopic gunner's sights used in earlier German tanks. Both models of the Tiger heavy tank also had an articulated telescopic sight, the TZF 9, with a magnification of x2.5, as did the Panther. The TZF 12a sight of the Panther was also designed by Leitz and represented a further development of the telescopic sight in having dual x2.5 or x5 magnification.

After the Second World War dual x3.5 or x7 magnification was also incorporated in the TSh 2-22 articulated telescopic sight of the Soviet T-54 tank and later also in the sight of the T-62 tank. In contrast to their use in German, Soviet and Italian tanks, articulated telescopic sights were not installed in British and US tanks until 1959 or 1960, and then only as single-magnification auxiliary sights.

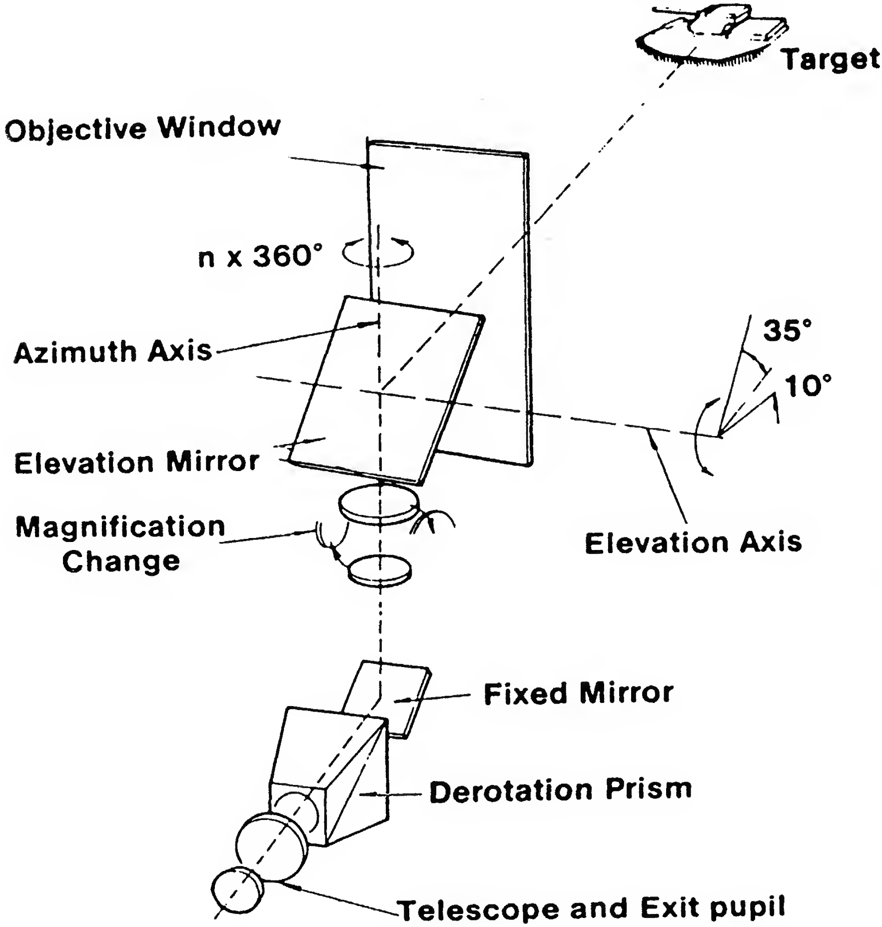


Fig. 5.5 Basic optical elements of a stabilised gunner's sight.

The sights were the No.26 telescope with x7 magnification which was mounted in the Chieftain, and the M105 telescope with x8 magnification which was mounted in the M60 tank.

At about the same time the Zeiss TZF 1A articulated telescope with x8 magnification was adopted for the German Leopard 1 as a secondary sight and another articulated telescope with x8 magnification, the M271, was adopted as the gunner's primary sight in the French AMX-30. A similar telescope was mounted for the same purpose in the more recently built AMX-32 and AMX-40 and in the late 1970s Vickers decided to use the Vickers Instruments' L30 articulated telescope with x10 magnification as the gunner's primary sight in the Valiant prototype. An articulated telescopic sight was chosen in this case and that of the three French tanks mainly because its objective can be fixed to the gun and because of the consequent elimination of the alignment and sighting errors which are associated with other sights (5.9, 5.10).

In the meantime British and US tanks were fitted with periscopic sights as their principal or only gunner's sights. The use of periscopic sights originated with the *Leicht* and *Grosstraktoren* built in Germany in 1929-1930, all of which had Zeiss periscopic sights with a head prism rotatable in elevation and linked mechanically with the gun. Similar Zeiss TWZF 3 periscopic sights with ×1.75 magnification were fitted in the first Swedish tank, the Strv m/31, and then in other tanks built in Sweden by Landsverk. From the mid-1930s onwards other sights of the same kind were also fitted in Soviet tanks such as the T-26B and BT-5 as well as BT-7. This was followed by the installation of the PT-47 periscopic sight with x2.5 magnification in the KV and T-34 tanks, but in their case only in addition to the TMFD telescopic sight. However, during the Second World War Soviet tanks ceased to be fitted with periscopic sights. Thus the T-34-85 which was introduced in 1943 was no longer fitted with the PT-47 but only with the TMFD sight.

But while they were being abandoned in Soviet tanks, periscopic gunner's sights were adopted in US M3 and M4 medium tanks. In the prototype of the M4 the sight was of the fixed type, like the original Zeiss periscopes, with a head mirror rotated in elevation by a linkage connected to the gun mounting. But when the M4 went into production this was replaced by the M4 periscope, which pivoted as a whole under the action of the linkage connecting it to the gun. A pendulous periscope of this kind linked to its 75mm gun had been adopted already in the M3 medium tank and similar periscopes continued to be used in US tanks until after the Second World War. During the intervening period they were improved optically to a considerable extent. In particular their magnification was increased from the inadequate level of x1.44 of the M4 periscope to x6 of the M10 periscope, which was introduced in M4 tanks towards the end of the Second World War and which was still fitted in M46 tanks in 1948 (5.11).

After they were abandoned in the United States pendulous periscopic sights continued to be used in British tanks. The first of them was the Centurion, which was originally fitted with the No.1 sight with two channels providing the same x6 and x1 magnification as the US M10 periscope. But as they were rearmed with the more powerful, 105mm guns, Centurions were fitted with sights with x8 magnification, and so were the early Chieftains. Subsequently, in keeping with the longer range capabilities of their 120mm guns, Chieftains and Challengers were provided with sights with x10 magnification.

Pendulous periscopes represent a relatively crude way of moving the line of sight in elevation but they are superior ergonomically at least to straight-through telescopic sights because their eyepieces move fore-and-aft rather than up-and-

down as guns are elevated or depressed, which requires less awkward head movements on the part of the gunner. They are also superior to the telescopic sights from the point of view of armour protection, as they do not require any aperture, or 'ballistic window', in the frontal armour of turrets. They are also more robust than fixed periscopes with tilting head mirrors but they are inferior to them as well as to articulated telescopic sights from the point of view of ergonomics because the latter have eyepieces that do not move.

The ultimate verdict on the pendulous periscopes is the fact that since the Second World War there has been an increasingly strong revival of the use of the alternative, fixed type of periscopic sight with a pivoted head prism or mirror. The first of the new generation of such sights was the US T35, which was originally installed in the turret of the T42 tank and which then went into service in the M47 medium tank as the M20 gunner's periscope. Similar sights were fitted subsequently in the M48 and M60 tanks but while the M20 periscope had a magnification of x6 and x1, like the M10 periscope, the M31 and M32 sights of the M48A3 and M60A1 have had the magnification of their high power day channel increased to x8 in keeping with the general trend.

In addition to the M20 gunner's periscopic sight, the M47 tank was also fitted with the M12 stereoscopic rangefinder, which is operated by the gunner and can be used not only for determining the range of targets but also to lay the gun on them. The rangefinder provides x7.5 magnification and only one half of it is used as a sight, when it becomes the equivalent of a periscopic sight laid on its side. Because of its magnification and the wide, 1.52m separation of its objectives, the rangefinder also provides the gunner with a very powerful binocular observation instrument which enhances stereoscopic effects and makes distant objects stand out in greater relief.

The development of an instrument which could be used by itself for rangefinding, gun-laying and binocular observation represented a major advance in the optical equipment of tank gunners. Nevertheless only Leopard 1 followed the example of the M47 tank in having a rangefinder operated by the gunner which was also the primary gun sight as well as being a powerful observation binocular. In this case the TEM 2A rangefinder has had an even greater magnification of x16 and an optical base of 1.72m. In other tanks optical rangefinders have not been allocated to gunners but to commanders, in spite of the fact that they distract the latter from their primary command functions. Moreover, most of the rangefinders have been of the coincidence type, which means that they are monocular rather than binocular instruments and therefore less effective for general observation. But the merits of the alternative approach of providing gunners with an optical instrument capable of performing three different functions, like the M12 and TEM 2A stereoscopic rangefinders, were invalidated when all optical rangefinders began to be superseded by laser rangefinders which are considerably easier to install as well as being much more accurate.

However, one feature of the installation of the M23 rangefinder in the M47 tank, namely its use as a gunner's periscopic sight with the head projecting out of the side of the turret, reappeared in the XM-1 prototype designed by General Motors, which had the gunner's primary sight mounted at the right side of its turret. This avoided the need to partially compromise the frontal armour of the turret or, alternatively, to accept a large projection out of the turret roof, which would interfere with the tank commander's vision. The side mounting of the sight was made particularly attractive by the size to which gunner's sights had grown by then. In particular, their entrance windows had become large, to allow for the

movement of the two-axis stabilised head prisms or mirrors which began to be incorporated in them. The windows were made larger still by the requirements of night vision, especially since the latter became based on thermal imaging and consequently required a germanium window separate from the glass window of the daylight vision and laser rangefinder channel.

But the example of the General Motors' XM-1 prototype has not been followed in other tanks with equally sophisticated and large gunner's sights. Instead, the sights have been fitted into the front of the turret, as in the Leopard 2, or mounted in the turret roof, as in the M1 tank produced by General Dynamics.

Apart from incorporating laser rangefinders and thermal imagers as well as stabilised head mirrors, the latest periscopic gunner's sights also provide greater magnification than earlier sights. Thus, the sight developed by Delco Electronics for the MBT-70, which was the first of the new generation of periscopic gunner's sights, incorporated a zoom telescope with magnification varying from x7 to x14. Zoom telescopes were not used in the sights developed subsequently by Delco Electronics for the XM-803 and the XM-1, which had telescopes with a dual magnification of x8 or x12.5 and x4 and x10, respectively. Dual magnification of x3 or x10 is also provided by the sight of the M1 tank but production versions of Leopard 2 have sights with a single magnification of x12, in spite of its prototypes having sights with dual magnification.

The magnification quoted for the different sights indicates the optical characteristics which have come to be required of gunner's sights. Their power has

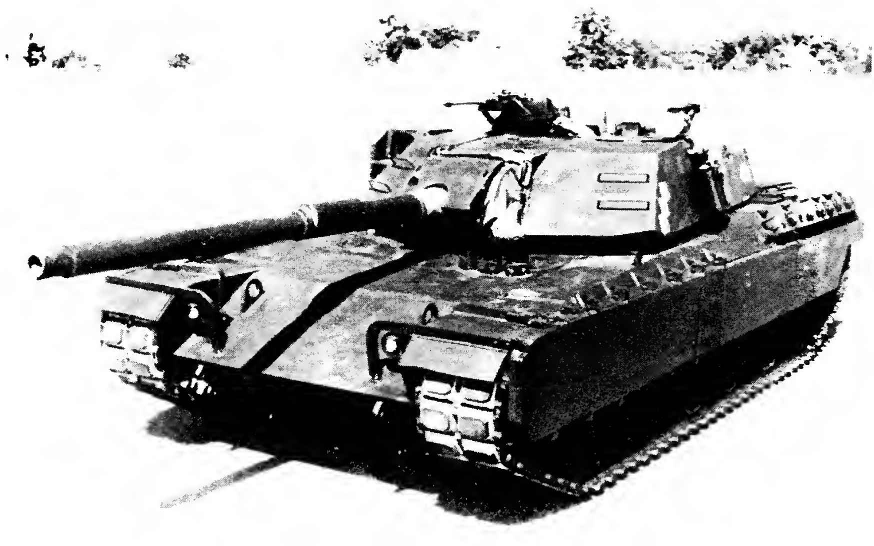


Fig. 5.6 General Motors prototype of the US XM-1 tank which had an independently stabilised gunner's sight at the right side of the turret. (General Motors Corp.)

obviously grown over the years but the x10 magnification which has been adopted in the latest of them is not as high as that of some of the sights which preceded them. This is due to it being a better compromise between the conflicting requirements of speed of detection and of detection at long ranges. In general, the time to detect a target increases with the magnification of the sight, because it takes longer to scan a search field when the magnification is high and the field of view is inevitably small than when the magnification is low and the field of view is correspondingly large. However, low magnification makes it difficult to detect targets at long ranges. Thus, unit power is the most effective, overall, at short ranges but to recognise targets at the maximum range of tank guns and beyond it is necessary to use a magnification of at least x8 and preferably x10.

A number of the simpler periscopic sights provide this degree of magnification and unit power viewing for target searching as well as general observation. This makes them superior in this respect to the telescopic sights with a single high magnification but still leaves much to be desired because of the big difference between the fields of view associated with magnifications of x10, or even x8, and x1. Thus, x10 magnification is associated with a field of view of about 6° while unit power is associated with fields of view of at least 24° and this can make it difficult or time consuming to switch from it to high power and still retain sight of the target. This is particularly true when, as is usually the case, the unit power window is separate from the high power eyepiece.

It is much more effective therefore to incorporate an intermediate degree of magnification, of x3 or x4, as has been done in the most advanced of the gunner's sights. This provides capabilities which overlap with those provided by the x10 magnification and make switching from one to the other relatively easy. Since they are associated with a field of view of 15° to 20°, magnifications of this order are suitable for observation and for target detection at up to the maximum range of tank guns and they provide sufficient resolution for the engagement of targets at other than long ranges. It is of interest to note that sights with similar dual magnification of x3 and x10 or x12 have also been developed for missile-armed helicopters.

But, for all the advances incorporated in them, even the latest gunner's sights are not as good as they might be in at least one respect, namely in their suitability for general surveillance. This calls for instruments that can be used for prolonged periods and therefore with a minimum of eye strain, which implies the use of both eyes. As it is, all the sights with two-axis stabilised head prisms or mirrors are monocular and although sights of this kind can not be made truly binocular they can, at least, be provided with biocular eyepieces.

Binocular vision can be provided, with all that this implies not only in terms of the fully relaxed use of both eyes but also of depth perception but at the price of stabilising the head prism only in elevation. This has been demonstrated by the Jungner sights developed for the S-tank but its consequence is that the stabilisation of the head mirror, or prism, in azimuth is not better than that of the cupola or turret in which the sight is mounted. A head mirror stabilised only in elevation is actually incorporated in the gunner's sight of the US M1 tank but, unlike the Jungner sights, it is monocular.

In the other sights the head elements have been independently stabilised in azimuth as well as elevation. This has done much to isolate the line of sight from both horizontal and vertical disturbances caused by tanks moving over rough ground. In consequence, gunner's capabilities are protected to a considerable extent against degradation by line of sight jitter caused by vehicle motion. The

independent two-axis stabilisation of the sights' head mirrors or prisms also allows much smoother target tracking than that which can be achieved by the turret traverse drives by themselves, particularly at low tracking rates.

5.7 Gunner's Auxiliary Sights

As gunner's sights have become more complex they have also become more susceptible to malfunctions and to safeguard against this as well as battle damage a degree of redundancy has been introduced in the form of a second or auxiliary gunner's sight.

Two gunner's sights appear to have been fitted as early as the mid-1930s in Soviet BT-5 tanks (5.12). They were certainly fitted in the KV and T-34 tanks, both of which had the periscopic PT-47 gunner's sight in addition to the TMFD articulated telescopic sight. The purpose of the second sight in these tanks is not clear: it may have been mainly for observation by the gunner over a wide arc, since the PT-47 sight could be used as a panoramic periscope. In any case the provision of a second sight was discontinued in later Soviet tanks such as the T-34-85 and the T-54, which were only fitted with telescopic gunner's sights. Even the T-72 has been fitted with only one gunner's day sight, but in this case it is no longer of the articulated telescopic type. Instead, the TPD-2 sight of the T-72 is periscopic, no doubt to avoid the need for an aperture for a sight in the front of the turret and to increase thereby its frontal protection.

In the meantime a new start to the use of a second gunner's sight was made in the US M4 medium tanks. In this case the second sight was of the simple, straight-through telescopic type and it was fitted because of trouble with the linkage of the M4 periscopic sight, which was the only sight mounted at first in the M4 tanks (5.13). As it had a x3 magnification, the M55 telescopic sight also compensated for the inadequate, x1.44 magnification of the M4 periscope.

Since then almost all US tanks, up to and including the M1, have had an auxiliary gunner's sight although it was only in the M60 that the awkward,

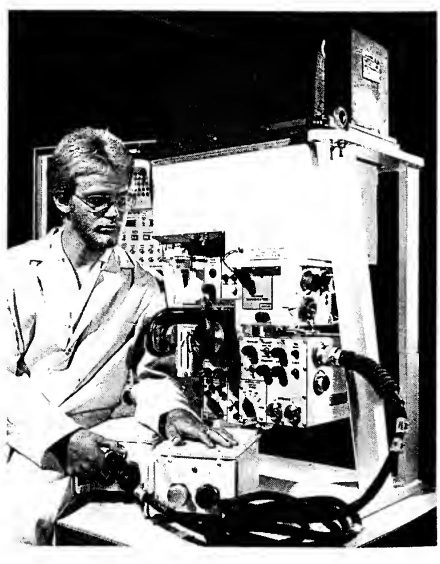


Fig. 5.7 Gunner's periscopic sight of the US M1 tank which is independently stabilised in elevation and incorporates a thermal imaging system as well as a laser rangefinder. (Hughes Aircraft Co.)

straight-through telescope was replaced by an articulated telescopic sight. An exception to this has been the M47 tank, which has the M20 periscopic sight in addition to the M12 rangefinder-cum-sight.

No auxiliary gunner's sights were fitted in German tanks until the Leopard 1, which has the Zeiss TZF 1A articulated telescopic sight with a x8 magnification in addition to the TEM 2A rangefinder-cum-sight. A similar auxiliary gunner's sight, the articulated telescopic FERO Z18, made by Leitz and having a magnification of x8, has been fitted also in Leopard 2.

On the other hand, no auxiliary gunner's sight has been fitted in any French tank, up to and including the AMX-40. This has also been true of British tanks until the advent of the Chieftain, which has been fitted with the No.26 and then the No.70 or No.80 auxiliary sights with x7 magnification. They and the sight fitted in the Vickers Valiant prototype have been the first and only articulated telescopic sights fitted in British tanks, because the successor to the Chieftain no longer has one. Instead, the Challenger is fitted with the No.87 auxiliary sight, which is of the periscopic type in order to avoid an additional aperture in the frontal armour of the turret. The No.87 periscope is of a simple, pendulous type with x10 magnification but instead of being permanently mounted in the turret roof it is normally stowed under it and only made to protrude through a small hatch and linked with the gun when required.

The auxiliary sight devised for the Challenger is probably the simplest and the least demanding of them so far as installation in a tank turret is concerned. But given a well designed primary sight that is reliable and easy to replace all auxiliary sights are something of a luxury and they add to the complexity as well as the cost of tanks. There are therefore strong incentives for dispensing with them and for providing tanks with redundant sighting systems in other ways. This has been done in a number of tanks by making the commander's sight capable of laying the gun or, more recently, by using for this purpose a night sight, where this is separate from the gunner's day sight.

5.8 Electro-Optical and Radar Systems

Whatever their type, optical instruments embody a direct optical path between the objective and the eyepiece. They can not be used, therefore, where such a direct path can not be provided and they are difficult to use when the objective and the eyepiece have to be separated to any extent.

These limitations of optical instruments can be overcome by inserting a closed-circuit television system between the objective and the eyepiece. In essence, this involves the combination of an objective lens with a television camera tube and the replacement of the eyepiece by a display unit, or monitor, containing a cathode ray tube. The camera tube converts optical images into electrical signals and these are transmitted to the cathode ray tube which regenerates the images. In consequence, the connection between the television camera and the monitor can be confined to a cable, which confers considerable freedom in their installation.

An important outcome of this freedom has been the possibility of mounting the camera on a remotely controlled gun and thereby aiming the latter. The use of a television camera for this purpose was proposed as early as 1952, in a US design study of a self-contained, 105mm gun pod to be mounted above a tank hull (5.14). A number of similar applications of television systems has been considered since then, particularly in connection with externally mounted guns, but they have been objected to because of the resolution of the usual 525 or 625-line television display

systems, which is inferior to that of optical systems.

The inferior resolution of television systems, as well as the loss of depth perception associated with them and the lack of colour cueing with the usual monochrome systems, have been somewhat less objectionable in connection with their possible use for driving. This began to be investigated in the United States, at the Aberdeen Proving Ground around 1961, inspired by the idea of operating tanks completely 'buttoned-up' in areas contaminated by nuclear radiation (5.15). No application has followed this but the use of television for driving remains a possibility.

More recently television has been considered for other reasons, namely on account of the difficulty of observing through the eyepieces of optical instruments when vehicles move at speed over rough ground. Under such conditions it can be easier to view a television display because of its larger size and the fact that the head of the observer does not have to be kept close to it. For this reason Delco Electronics incorporated a television system with a high-resolution cathode ray tube in the gunner's sight built for the US High Mobility/Agility Test Bed of the late 1970s. For similar reasons a Pietzsch Staget sight has been installed in some German high-powered test vehicles. This sight incorporates a stabilised television camera and is used in conjunction with a remotely located video display unit.

A different potential advantage of television systems is that, once they are installed, the video signals which their cameras generate are available for two further purposes. One is automatic target tracking with the aid of a video tracker, which is discussed in Chapter 7. The other is image processing, by means of which targets can be detected automatically and which can provide enhanced cues on the video display.

The use of television for these two purposes is still in its early stages. In the meantime television is used for night vision, either as the basis of the low light level television systems or as one of the ways of displaying the output of thermal imagers, both types of which are discussed in Chapter 6. Most television systems incorporate vidicons as the camera tubes although some use instead silicon intensifier (SIT) camera tubes. However, some video cameras already use solid-state, charge-coupled device (CCD) image sensors which, unlike the camera tubes, do not need a scanning electron beam. Solid-state video cameras are now available in colour as well as monochrome form and this, together with their small size, is bound to lead to their increasing use.

Thermal imagers, with which closed circuit television is often employed, were originally developed for night vision but they have come to be used also for daylight target acquisition. In particular, the wavelengths at which they operate enable them to detect targets through haze, dust and smoke and their ability to detect small temperature differences enables them to detect targets even when they are well camouflaged and therefore difficult to acquire visually. The use of thermal imagers for surveillance and target detection in daylight still has to be fully exploited, by such means as the blending or comparing of the thermal and visual images to enhance the probability of detecting targets, but they have already increased considerably the target acquisition capabilities of tanks.

However, the use of thermal imagers for target acquisition has produced a response in the form of screening systems which can obliterate the thermal signatures of tanks. One way in which this can be done is by a combination of absorption, scattering and reflection of the thermal radiation from tanks, which is produced by aerosols dispensed by grenade launchers. This is similar, in principle, to the way in which conventional smoke screens operate but to be effective against

thermal imagers it requires a considerable quantity of relatively large particles to be suspended in the air and this is not easy to achieve, particularly within the limited discharge capabilities of the launchers mounted on tanks.

The alternative is to discharge grenades which burst to produce a cloud of material emitting infrared radiation. This prevents thermal imagers from detecting a tank behind the radiating cloud. The screening material contained in the grenades is effective against thermal imagers operating at wavelengths of 3 to 5 and 8 to 14 microns and it also produces a visual screen. Some of the systems produce a screen which begins to form one second from the instant of firing and lasts for up to one minute, maintained by the firing of successive grenades.

In addition to multi-band smoke screens, fog, rain and snow can also reduce the effectiveness of thermal imagers. As a result, additional or alternative methods of acquiring targets on the basis of millimetre wave radar have been explored since the late 1970s. Radar has been tried in tanks before this but only to detect the movement of other vehicles, particularly at night or under conditions of poor visibility. Its use for that purpose is exemplified by RAPACE – an acronym for *Radar Pour Acquisition de Chars Ennemis* – developed in the late 1960s in France and tried on AMX-30 tanks. RAPACE could detect vehicle movement at more than 5km but it operated in the centimetre waveband at about 20GHz and lacked sufficient resolution to be used for target acquisition.

The high degree of angular resolution required to produce images sufficiently detailed for target acquisition did not become available until the development of millimetre wave radar in the late 1970s. Its actual wavelengths are governed by the propagation 'windows' or, in other words, by the attenuation of millimetre waves by atmospheric gases, which is at a minimum at wavelengths of 8.5, 3.2, 2.1 and 1.4mm, or frequencies of 35, 94, 140 and 220 GHz, respectively. The shortest wavelengths, or highest frequencies, give the highest degree of angular resolution but for lack of the associated equipment frequencies of 94 GHz have been used at first.

The first attempt to use millimetre wave radar in tanks is represented by the Surveillance and Target Acquisition Radar for Target Location and Engagement, or STARTLE, programme initiated around 1978 by the US Army's Night Vision and Electro-Optics Laboratory.This programme demonstrated the feasibility of acquiring targets by means of millimetre wave radar and some of its advantages over other systems used in tanks.

In general, millimetre wave radars do no have the same all-weather capabilities as more conventional centimetre wave radar but they are better able to detect and to track tank targets through fog, rain and multi-band smoke screens than thermal imaging devices. However, their resolution is inferior to that of thermal imaging systems and, unlike the latter but in common with other radar systems, they are active. This means that they are detectable, which is a serious tactical disadvantage.

Their active nature apart, millimetre wave radars have capabilities which in many respects complement those of thermal imagers. The most effective way of using them is likely to be therefore in combination with thermal imagers and between them they should be able to cope with a much wider range of operational and environmental conditions than either type of system could do by itself. The integration of millimetre wave radar with thermal imagers became one of the latest developments to be pursued, an example of this being the US Army's Multispectral Target Acquisition System programme, which followed the STARTLE programme (5.16).

5.9 References

5.1 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, pp.128-129.

5.2 P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978, p.30.

5.3 J Bingham, *French Infantry Tanks*, part I, AFV/Weapons Profile No.58, Profile Publications, Windsor, 1973.

5.4 A Gleichen, *The Theory of Modern Optical Instruments*, Stationery Office, London, 1918.

5.5 W Esser, *Dokumentation über die Entwicklung und Erprobung der ersten Panzerkampfwagen der Reichswehr*, Krauss-Maffei, Munich, c.1979, pp.24, 43 and A.5.5.

5.6 W Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, p.291

5.7 *Integrated Small Craft Weapon System*, Delco Electronics, Santa Barbara, 1975, p.23.

5.8 F B Patrick, 'Military Optical Instruments', in *Applied Optics and Optical Engineering*, ed. R Kingslake, Vol.V, Academic Press, New York, 1969.

5.9 R L MacDonald, *Innovative Features of the New Vickers Valiant Main Battle Tank*, Symposium – High Technology in Defence, Brighton, 1981.

5.10 de Bernardi, *Les Techniques d'Engagement et les Conduites de Tir*, Conference – La Rapidité d'Action dans le Combat Blindé, Satory, 1983.

5.11 R P Hunnicutt, *op.cit.*, pp.12, 128 and 258.

5.12 J F Milsom, *Soviet BT Series*, AFV/Weapons Profile No.37, Profile Publications, Windsor, 1971.

5.13 R P Hunnicutt, *ibid.*, p.139.

5.14 *A History of Automatic Loading Equipment*, Report No. RR-13, Ordnance Tank-Automotive Command, Centre Line, Michigan, 1960, pp.81-84.

5.15 'Tank Driving by Television', *Armor*, Vol.70, No.5, September-October, 1961, pp.42.43.

5.16 P Johnson, 'Tank Vision Systems of the Future', *Military Technology*, No.6, 1984, pp.49-56.

Chapter 6

Illuminating and Night Vision Systems

6.1 Tank-Mounted Searchlights

The difficulty of driving tanks and the even greater difficulty of acquiring targets from them in the dark limited their use at night to a relatively small number of occasions during the first quarter of a century of their existence. The first night action by tanks actually took place on 22 June 1918, when five British tanks cooperated with infantry in a raid on German positions near Bucquoy in France (6.1). But this proved to be an isolated event and it was only during the exercises which followed the formation in Britain of the Experimental Mechanized Force in 1927 that further steps were taken in the use of tanks at night (6.2). However, five years later even a leading proponent of tanks still considered that, in general, night attacks by them were 'unlikely' (6.3). Ten years later still a US armoured force manual reflected a similar view by declaring that "the use of tank units in night operations will be limited" (6.4).

At the time the only means available to help tanks fight at night were illuminating, or star, shells and searchlights. The possible use of the latter in tank operations began to be explored in Britain in 1927 (6.5). It appears to have been inspired by the earlier use of searchlights in naval operations and was intended to dazzle or to blind the enemy rather than to provide the illumination which tanks needed to move and to acquire targets at night. But whether they dazzled the enemy or not, searchlights were obviously very conspicuous and vulnerable to enemy fire. In consequence, the idea of using them in tank operations led in Britain to the development of special tanks with searchlights mounted in well-armoured turrets.

The development of searchlight tanks that would dazzle the enemy began in 1933 with the formation of a syndicate headed by Commander O de Thoren of the Royal Navy, who had already proposed the use of searchlights on tanks during the First World War. The syndicate also included General J F C Fuller, who acted as its military adviser and who endorsed what he called 'attack by illumination' to the point of arguing, somewhat naively, that it was a means of winning wars (6.6).

Demonstrations arranged by the syndicate in 1936 and 1937 impressed the War Office to the extent that it took up the idea of a special searchlight tank and ordered the design of a special turret mounting a searchlight, which was completed in 1939. Six more turrets of an improved type were built by April 1940 and the searchlights mounted in them proved so difficult to put out during firing trials that

300 turrets were ordered for installation on Matilda infantry tanks in place of their normal gun turrets.

The turrets contained two chambers, one of which was occupied by a high-powered carbon arc lamp and the other by the searchlight operator. The front face of the turret had a slit about 60mm wide and 600mm high through which the searchlight projected a beam that could illuminate a width of 340m at a distance of 1000m. A powered armour plate shutter opened and closed the slit making the beam flicker and this in turn made aiming at the searchlight more difficult. It was also hoped that the flicker, together with the intensity of the light beam, would have a blinding effect but this did not prove to be the case (6.7).

For reasons of secrecy the searchlight tanks were given the code name of Canal Defence Light, or CDL, tanks and the British Army formed no fewer than two brigades of them during 1941 and 1942. However, they were only used once, and on a very small scale, in 1945, when 24 of them covered an assault crossing of the Rhine in the closing stages of the Second World War.

By then the Matilda CDL had been superseded by the Grant CDL, which consisted of the US-built M3 medium tank fitted in Britain with the same searchlight turret as the Matilda. This type of searchlight tank was also adopted in 1943 by the US Army which followed the example of the British Army and formed six battalions of the M3 CDL tanks. But although 497 CDL tanks were built in the United States, only 64 of them were ever used – in the defence of the Rhine crossings in the closing stages of the war (6.8).

Thus the special searchlight tanks were never fully used. The cause of it is generally held to be the excessive secrecy which surrounded their development and which inhibited their employment. However, searchlight tanks also suffered from the fundamental disadvantage of being a very specialised, limited-purpose equipment which, like others of this kind, would seldom be where its peculiar characteristics were wanted or where it could be used as intended. Their development was, therefore, highly questionable and, even if it had not turned out to be such a fiasco,

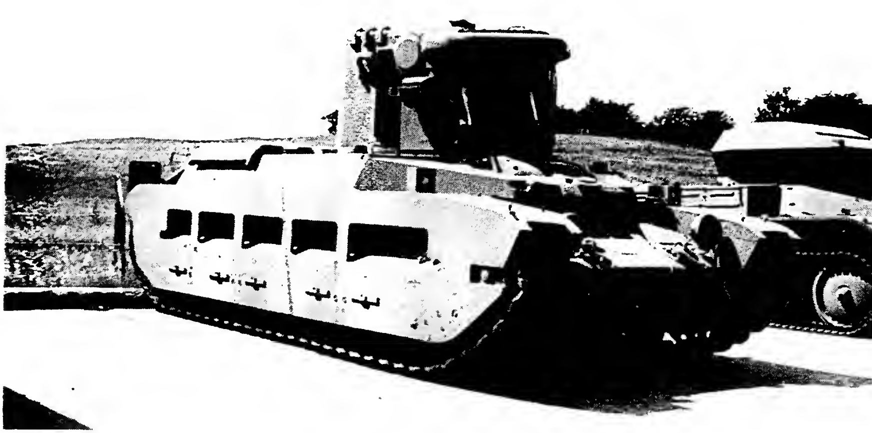


Fig. 6.1 CDL tank consisting of a searchlight turret on a Matilda infantry tank chassis.

the effort devoted to them could have been far better employed in developing standard tanks. This was particularly true in Britain, where there was much room at the time for the improvement of the standard tanks. But the history of the CDL tanks also provides a more generally valid example of a wasteful misdirection of resources to narrowly specialised equipment that was of very limited use.

For all practical purposes, the use of special searchlight tanks came to an end in 1945. But five years later there was a brief revival of interest in them in the United States, brought about by the outbreak of the war in Korea. The final US development of the CDL tanks based on the M4A3 medium tank was reconsidered as the T52 searchlight tank but it was soon discovered that its cost was equivalent to that of equipping four battalions of tanks with modified commercial searchlights. These 460mm diameter searchlights were relatively vulnerable but even if a number of them were knocked out by enemy fire their cost was still considerably less than that of one searchlight tank. In consequence, special searchlight tanks were very wisely not considered further. Instead, standard tanks were fitted with modified commercial searchlights and they were used in Korea in 1952–53 to provide direct, visible illumination for aimed fire (6.9). They proved effective on a number of occasions and their use was accepted as a normal part of US tank tactics. To reduce their vulnerability, it was recommended that any one searchlight be turned on for only 15 seconds and then switched off, when the searchlight of another tank would be switched on, thereby making it more difficult for the enemy to aim accurately at them (6.10).

Direct visible illumination became possible for many tanks during the 1960s and 1970s with the widespread installation on them of searchlights. But by then search lights had acquired a dual purpose, namely that of providing infrared as well as visible illumination. In fact, infrared illumination became their more important purpose but their use for visible illumination continued to be regarded as possible.

To reduce its vulnerability, the searchlight originally installed on the Israeli Merkava was not mounted on the front of the turret as on other tanks, but at the back of it, so that its beam was projected upwards and only reflected into the horizontal direction above the turret by means of a mirror mounted on a short mast. The searchlight of the Leopard 2 prototype was also mounted at the back of the turret but in this case it was on an arm, which raised it above the turret roof when required for illumination.

Such refinements made searchlights less vulnerable but did nothing to make their use less conspicuous. This remained the major disadvantage to their use on tanks and led to them being abandoned with the introduction of passive night vision systems in the 1970s and 1980s.

In addition to their installation on tanks for direct illumination, searchlights have also been used to provide indirect illumination. In this case their light has been reflected off low-hanging clouds to produce 'artificial moonlight' which illuminates larger areas than direct illumination and allows the searchlights to be located behind cover. However, indirect illumination requires more powerful searchlights than those generally mounted on tanks and, like the direct use of searchlights, has become uneccessary with the advent of image intensifiers and thermal imagers.

6.2 Illuminating Shells and Bombs

Until the advent of tank-mounted searchlights the only means of helping tanks to fight at night were illuminating shells. These can provide intense illumination of

selected target areas but the illumination produced by any one shell is short-lived. Moreover, in general, tanks have not been supplied with illuminating rounds and have not been able therefore to fire illuminating shells themselves. Instead, illuminating shells have been fired by the artillery, which inevitably creates problems of cooperation and, of course, requires that artillery be available to support tanks.

Nevertheless, artillery continues to be supplied with illuminating rounds and they are available therefore to help tanks in appropriate circumstances. Illuminating shells are produced for guns of up to 155mm and they contain a flare with a parachute which reduces its rate of descent after it has been ejected out of the shell body above the target. In the case of a typical 155mm shell the rate of descent of the flare is 4 to 5 m/s and it burns for a total of about 60 seconds. The average output of the flare is 2×10^6 candelas and after burning for some time it can, from a height of 350m, illuminate a circular area with a diameter of approximately 1000m at a light level of 5 lux, which corresponds to the illumination on a very bright day.

An illuminating shell similar to those fired by the artillery has been produced for the 105mm F1 gun of the French AMX-30, which has been one of the few tanks to have such ammunition available for it. The flare of this shell is inevitably smaller than those of the 155mm shells but for about 35 seconds it can illuminate at a light level of 5 lux an area with a diameter of 300m and at 1 lux to a diameter of 900m.

An illuminating shell has also been developed in Germany for the 105mm L7 tank gun. But this shell is very different from those fired by the artillery and the AMX-30 tank. In particular, it does not contain a parachute and is not, therefore, intended to explode over a target area to illuminate it from above. Instead, it is meant to be fired behind the target, where its illuminating charge is ejected to fall and burn on the ground, making the target stand out in silhouette against the bright background created by the burning charge. It is suited therefore to illuminating specific targets whereas the other shells are designed to illuminate relatively large target areas (6.11).

But, whatever their technical or tactical merits, illuminating shells suffer from the major disadvantage that their use reduces still further the already small number of rounds which tanks carry for engaging targets. For this reason their use by tanks is bound to be limited, if it continues at all.

In the absence of illuminating rounds for tank guns and in view of the uncertainties about the ability of the artillery to fire such rounds on time, if at all, some tank units have incorporated detachments of mortars, which can fire illuminating bombs. Those fired from typical 81mm mortars are similar in principle to illuminating shells and like the latter contain a parachute to delay the descent of the flare. Their flares burn for 35 to 40 seconds and have an output of about 6 to 8×10^5 candelas, which enables them to illuminate almost the same area as 105mm illuminating shells.

Mortar detachments of tank units offer the advantage of being able to support tanks more closely and provide illumination at less cost than the artillery but they require additional vehicles and manpower. Moreover, their employment again results in a separation between tanks and the source of illumination, with all that this implies in terms of problems in coordination and timing.

In consequence, it is more effective to use mortars mounted on tanks. This has been done since the late 1970s with the development by Bofors of the Lyran illuminating system which consists in essence of a simple 71mm mortar and illuminating bombs. The bombs have a range of 1300m and contain a parachute

which reduces the rate of descent of their flares to about 3 m/s. The flare has a mean output of 6 x 10^5 candelas and burning time of 30 seconds, after about 25 seconds of which it provides 5 lux illumination over an area having a diameter of 630m. The illumination time of at least 25 seconds is long enough for tank crews to acquire and engage most targets and the 5 lux light level provides the necessary conditions for well-aimed fire. To eliminate the need for reloading the mortar every time a bomb has been fired it is desirable to have two to four mortars on each tank, which can be done without any particular difficulty because of the relative simplicity of the Lyran mortars.

Although the Lyran mortars can not fire as far as standard mortars and, even less, guns, their range is sufficient for most tank engagements and they provide tanks with a source of illumination which is autonomous and immediately available. They eliminate the possibility of delays that can arise when illumination is provided for tanks by other units and tanks can fire them with little risk of exposing their positions.

The use of small mortars by tanks has been taken a stage further in the Israeli Merkava, the Mark 2 and 3 versions of which have a turret-mounted 60mm mortar. The latter can be loaded from inside the turret and it can fire not only illuminating bombs but also others, including high explosive bombs, to a range of 3000m.

6.3 Active Infrared Systems

The first major advance in night operations on the use of illumination provided by various sources of visible light came as a result of the application of infrared image converters. These respond to the thermal radiation emitted or reflected by objects, the wavelength of which is outside the visible, 0.4 to 0.7 micron range of the spectrum, and convert its pattern into an image visible to the human eye.

The conversion can be accomplished by an image converter tube containing a silver-oxide-caesium photocathode, which has been given the spectral response designation S-1, and a fluorescent screen. When the thermal, or infrared, radiation falls on it the cathode emits electrons which are electrostatically focused on to the screen, causing it to emit light and in this way a visible image is formed from the original infrared pattern. Thus infrared image converters make it possible to see in the dark. However, the spectral response of the S-1 photocathode is limited in practice to between 0.8 and 1.2 microns and few objects of military interest produce a significant amount of radiation in that range (6.12). In consequence, night vision devices based on image converters can not, in general, operate on the basis of the radiation emitted by targets. Instead, they have to rely on the reflected radiation provided by infrared sources, which need to be used in conjunction with them to illuminate the scene.

The source of the illumination can be tungsten filament lamps fitted with filters to cut off all radiation with a wavelength of less than 0.8 micron, so that they can not be detected by the unaided eye. An alternative source are Xenon arc lamps, which have been widely used as tank searchlights. The reasons for the widespread use of Xenon searchlights are their brightness and their spectral characteristics extending to a wavelength of about 1.5 micron, with several strong lines in the region in which image converters operate. A filter is used again to block all visible light when the Xenon searchlight is used for infrared illumination and without the filter it can be used as a normal, visible light searchlight.

Because they first illuminate the scene and then detect the reflected radiation,

Fig. 6.2 Soviet T-62 tank with two searchlights of its active infrared night vision system.

Fig. 6.3 British Chieftain tank with a searchlight at the side of its turret to provide white light or infrared illumination. (Ministry of Defence, Crown Copyright Reserved)

systems based on infrared image converters are active systems, in contrast to passive infrared systems which do not emit any radiation but only sense the radiation naturally emitted by targets. As they provide their own illumination, active infrared systems are independent of ambient light so unlike some of the passive systems, they are effective even when the scene is very dark. However, they suffer from the very serious disadvantage that their searchlights can be easily detected by an enemy with infrared sights. Moreover, the effective range of active infrared systems is reduced considerably by fog and smoke. Under favourable atmospheric conditions the maximum range varies from 80m or less for simple night driving systems with infrared headlights of about 100W, to 1000m or more for gunners' sights used in conjunction with 1 to 2 kW xenon searchlights.

Active infrared systems were first developed for tanks in Germany and were used originally, with some success, against Soviet tanks in 1944 (6.13). In particular, some Panther tanks were fitted with image converters and they operated with 600mm infrared Uhu searchlights mounted on Sd.Kfz.251/20 armoured half-tracks (6.14). At about the same time active infrared night driving equipment was also introduced in German tanks.

The Soviet Army was the first to follow the German example and within ten years of the end of the Second World War began to fit its tanks with active infrared equipment. The first Soviet tank built with such equipment appears to have been the T-54B but since the late 1950s it has been fitted, or retrofitted, in other Soviet tanks (6.15). It was still fitted in the T-72, which entered service in the early 1970s, and continued to be used on that tank as well as others during the 1980s.

The only two armies which were in a position to follow the German example immediately after the Second World War, namely the US and the British, did not do so. In fact, they were very slow to adopt active infrared equipment for their tanks. Thus, it was only during the mid-1960s that British Centurion tanks began to be retrofitted with infrared driving lights, searchlights and infrared sights. Similarly, it was only around 1965 that M60A1 tanks with active infrared equipment began to be used by the US Army (6.16).

New tanks which began to come into service at about the same time were fitted with active infrared equipment from the start. They included the British Chieftain, German Leopard 1 and French AMX-30, all three of which had searchlights capable of illuminating targets at ranges of up to 1000m, or more, in the infrared mode. Active infrared equipment was also fitted in the US M551 Sheridan, which was designed somewhat later than the previous three tanks, and a xenon searchlight was still fitted in the US-German MBT-70, which was designed between 1964 and 1966 (6.17). However, MBT-70 was also fitted with other passive night vision devices and from then on active infrared equipment began to lose ground.

Many of the installations of active infrared equipment have been of a primitive nature partly because they were in tanks not designed for it. For instance, the use of the infrared gunner's and commander's sights in tanks like the Centurion or even the Chieftain required fitting them in place of the day sights each time they were to be used. However, Soviet tanks from the T-54B onwards have been permanently fitted with the TPN 1-41 infrared periscopic gunner's sight in addition to the TSh 2-22 telescopic day sight. This was improved upon in the US M60A1 by the installation of the M32 gunner's periscope in which an infrared sighting system was combined with a daylight sighting system (6.18). A similar sight, the PERI Z-11, was produced in the early 1970s in Germany by Leitz for the Marder infantry vehicle. In France SOPELEM developed a driver's periscope

which contained both infrared and daylight viewing channels and thus eliminated the need to replace a day periscope by an infrared persiscope whenever the latter was required for driving at night. The periscope was installed in the AMX-30 tank but the practice of using separate day and night driver's periscopes and replacing them by each other, as required, has continued in other tanks.

6.4 Image Intensifiers

Although active infrared equipment made it possible to drive tanks and to acquire targets in the dark, its use suffered from the basic disadvantage mentioned earlier that the sources of illumination which form part of it can be easily spotted by an enemy who has infrared image converters. Moreover, the searchlights that go with it are awkward to mount on tanks, because of their relatively large size, and are vulnerable to damage. In consequence, the introduction of infrared image converters was followed by efforts to develop image tubes with more sensitive photocathodes which would not require artificial illumination to form images at night. This led in the 1960s to the introduction of passive image intensifiers, which only require the low level of illumination provided by starlight to form visible images of the scene.

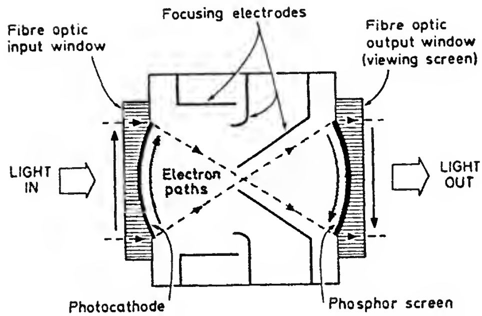
In essence, an image intensifier consists of a photocathode on which the radiation reflected by the scene is received, a system focusing the electrons emitted by it and a phosphor screen for displaying the image. The photocathodes are generally of potassium, sodium, caesium and antimony and have the spectral designations S-20 or S-25 (6.19). Apart from the spectral designation, image intensifiers are commonly classified by the size of the photocathode-aperture, which in the case of tanks is generally 25mm.

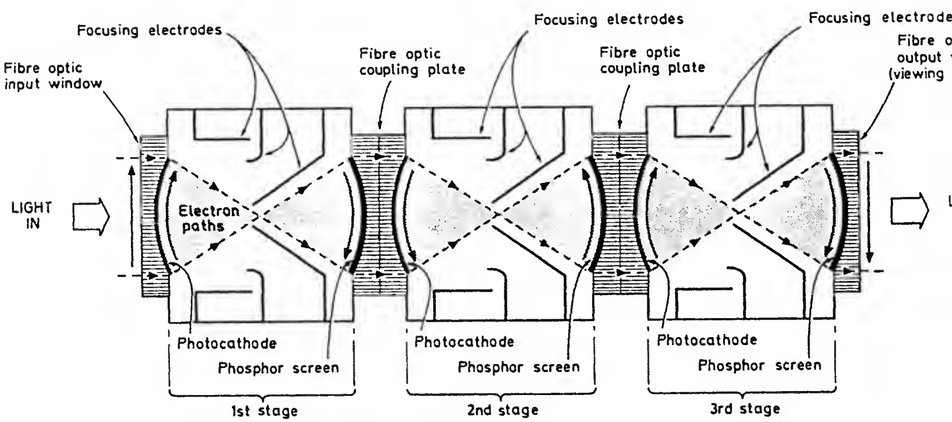
The first generation of image intensifiers with single stage tubes provided luminence gains of up to 2000, which is sufficient for driving with them under starlight conditions (6.20). Under such conditions the light level is approximately 10^{-3} lux and the first-generation, single-stage image intensifiers have an effective range of up to 100m. This is obviously inadequate for acquiring and engaging targets, which requires a luminence gain of at least 10^4, or what amounts to converting starlight into twilight.

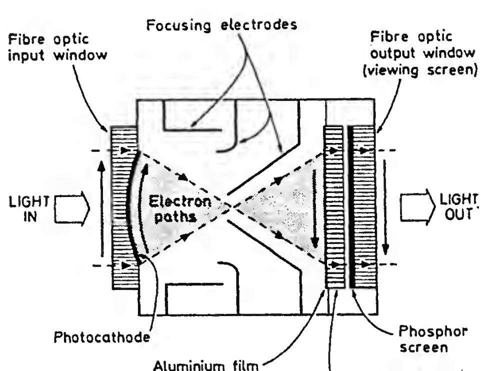
To achieve higher gains, first-generation tubes were connected in series by fibre-optic coupling plates to form three-stage cascade tubes. These provide gains of about 10^5, which is sufficient for the detection of targets at useful ranges even under conditions of overcast starlight. However, three-stage tubes are rather heavy and bulky. Moreover, their three phosphor screens cause images to persist to a noticeable extent, which can be distracting when the scene is moving, and bright sources in their field of view can cause image white-out.

The shortcomings of the first generation of image intensifiers were overcome by the development of micro-channel plates, which led to the second generation image intensifiers. The latter have single stage tubes but with a micro-channel plate in front of the phosphor screen. The plate consists of an array of minute glass tubes with an emissive internal coating and a high potential applied between their ends, which causes electrons emitted by the photocathode and entering the tubes to release other electrons. As a result the density of the electrons on the output side

Fig. 6.4 Three types of electrostatically focused image intensifiers : top, single-stage type, middle, three-stage cascade type and, bottom, microchannel inverter type. (Mullard Ltd.)


Focusing electrodes
Fibre optic
input window
Fibre optic
output window
(viewing screen)
LIGHT
IN
Electron
paths
LIGHT
OUT
Photocathode
Phosphor screen


Focusing electrodes
Fibre optic
input window
Fibre optic
coupling plate
Focusing electrodes
Fibre optic
coupling plate
Focusing electrodes
LIGHT
IN
Electron
paths
Photocathode
Phosphor screen
1st stage
Photocathode
Phosphor screen
2nd stage
Photocathode
Phosphor screen
3rd stage


Focusing electrodes
Fibre optic
input window
Fibre optic
output window
(viewing screen)
LIGHT
IN
Electron
paths
LIGHT
OUT
Photocathode
Aluminium film
Phosphor
screen
Microchannel plate

of the plate is much greater than on the input side and a correspondingly brighter image is formed on the viewing screen. Thus, micro-channel plate image intensifiers provide high gains without the need for cascading. The luminence gains of second-generation image intensifiers are actually of the same order as those of three-stage first-generation intensifiers but they are smaller and enjoy other advantages.

There is also a third generation of image intensifiers with single-stage tubes which combine micro-channel plates with negative electron affinity gallium-arsenide photocathodes. Compared with the first and second generation intensifiers they are more sensitive and capable of higher resolution, which means that their effective range is about 25 per cent greater (6.21).

The low luminence gains of the early, first-generation, single stage image intensifiers and therefore their limited effective range confined their use to driver's periscopes. Thus, some tanks were provided with image intensifier periscopes for their drivers while they retained active infrared sights for their gunners. This was the case, for instance, with the Chieftain and Leopard 1 when their original active infrared driver's periscopes were replaced by passsive image intensifier periscopes.

The provision of the passive driver's periscopes constituted a major advance in the night-time mobility of tanks as it enabled them to be driven in the dark without

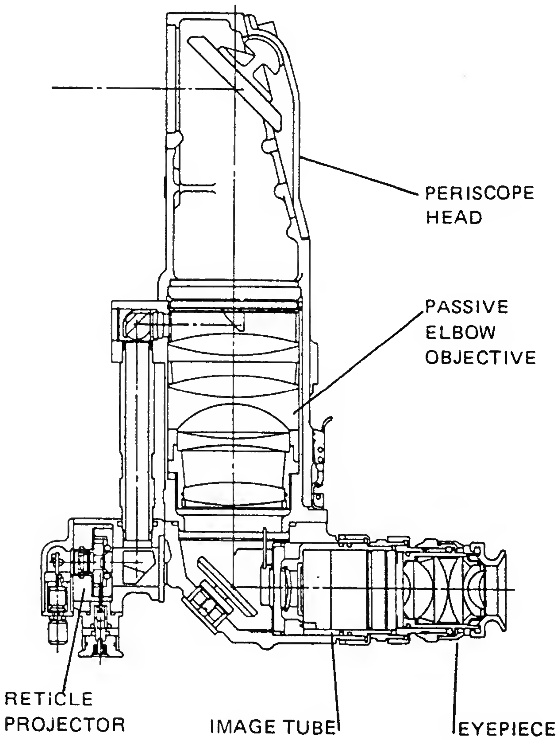


Fig. 6.5 Cross section of a NV31 gunner's periscope incorporating an image intensifier. (Optic-Electronic Corp.)

the risk of being detected by an enemy equipped with infrared image converters, or image intensifiers. At first passive driver's periscopes resembled the active periscopes in being binocular. In other words, they contained two separate optical channels and two image intensifier tubes, which provided stereoscopic vision and, therefore, depth perception. The latter has been considered important for driving at speed but periscopes with binocular eyepieces require drivers to keep their eyes close to them. In practice this means that they have to keep their heads against the brow-pads of the periscopes, which is tiring, particularly when vehicles are moving over rough ground. Because of this, more recently developed driver's periscopes have a single biocular eyepiece, which produces a single, relatively large display for two-eye viewing. Moreover, the distance from which the biocular eyepiece can be viewed, or eye-relief, is considerably greater than with the binocular periscopes, which eliminates the need for the driver to keep his head against the brow-pad of the periscope. As a result, periscopes with biocular eyepieces are less fatiguing. They are also simpler and, in principle, less expensive because a biocular eyepiece implies a single optical channel and only one image intensifier tube per periscope.

Periscopes of this kind are exemplified by the AN/VVS-2 driver's periscope of the US M60A3 and M1 tanks. Their second-generation, micro-channel plate tubes with 25mm photocathodes have a minimum gain of 25 x 10^3. The luminence gain with such micro-channel plate tubes can be as high as 6 to 7 x 10^4, which makes them greatly superior to the single-stage, first-generation tubes and is more than adequate for driver's periscopes. The single channel periscopes with biocular eyepieces do not, of course, provide stereoscopic viewing but this does not appear to have had a significant effect so far as driving is concerned (6.22).

The advent of the three-stage cascade tubes made it possible to extend the use of the first-generation image intensifiers to the acquisition and engagement of targets. However, the resulting gunner's and commander's sights have been undesirably large. This has been clearly illustrated by the SS 100 articulated, telescopic gunner's sight development by Rank Precision Industries for the Scorpion light tank.

Like the early active infrared sights, the original image intensifier gunner's sights such as the SS 100 have been entirely separate from the gunner's day sights, while commander's image intensifier sights such as the SS 120 produced for the British Challenger tank, could only be used by replacing the day sight, like the driver's periscopes. However, such primitive practices have not had to be followed with more recent gunner's and commander's sights, which incorporate day and night systems in a single unit and do away, therefore, with the need for separate sights or for replacing day and night sights by each other.

In fact, the introduction of micro-channel plate tubes made it possible to incorporate second-generation image intensifiers in sights originally designed to contain day and active infrared systems by direct replacement of the latter. This has been done, for instance, with the M32E1 periscopic sight fitted in the US M60A1, which is an M32 sight with the infrared image converter elbow replaced by a 25mm second-generation image intensifier elbow.

Gunner's and commander's sights with second-generation image intensifiers and suitable optics make it possible to acquire targets at up to 1300 or even 1500 metres under starlight conditions and 2600 to 2700 metres under full moon conditions, when the light level is 10^{-1} lux. However, such ranges are only achieved under favourable meteorological conditions. Under less favourable conditions and on very dark nights, when the light level is only 10^{-4} lux, the ranges are

considerably shorter.

The effective range of image intensifiers can be increased by illuminating the scene with infrared searchlights, because their spectral response extends to the wavelengths at which the searchlights operate, although they are designed for optimum performance at the lower wavelengths of 0.4 to 0.7 micron. But the use of searchlights implies giving up the advantages of the passive mode of operation and accepting the disadvantages associated with active systems, including the ease with which the infrared searchlights can be detected by an enemy equipped with image intensifiers.

A more sophisticated active technique, which has also been tried, involves the use of a pulsed laser instead of an infrared searchlight. This has given night sights a longer effective range than those achieved under starlight conditions not only with unaided image intensifiers but also when they were used in conjunction with infrared searchlights (6.23). The image tube used in conjunction with the laser illuminator is electronically controlled, or gated, so that it only admits returns from the distance at which the target to be observed is located and this eliminates foreground and background clutter. But searching for targets at unknown ranges requires moving the range gate through the ranges of the potential targets. In any case, the use of a pulse gated laser has been confined to the gunner's sight developed by Delco Electronics for the US XM-803 tank. In this particular case the laser was used in combination with what was described as an image intensifier but, in fact, incorporated a S-1 photocathode and produced images from the reflected infrared radiation. The sight of the XM-803 represented therefore an extension of the use of infrared image converters rather than that of image intensifiers.

6.5 Low Light Level Television

In addition to image intensifiers there is also another category of passive night vision devices which operates on the basis of the low levels of illumination provided by starlight. This category consists of low light level television systems which have been developed at about the same time as the image intensifiers and are, in principle, an alternative to them.

A typical low light level television system consists in essence of a vidicon and a display monitor. The vidicon is a small, television type camera tube with a photoconductive target behind a faceplate at one end and an electron gun at the other end (6.24). The gun produces a beam of electrons which scans the rear surface of the target and, as the radiation from the scene causes local changes in the conductivity of the photoconductive material of the target creating a positive charge image the beam discharges each picture element in turn. Discharge electrons then flow into electronic circuits which produce video signals and these are transmitted to the monitor with a cathode ray tube that displays the scene being viewed.

Low light level television systems have been developed chiefly in France, where Thomson-CSF started working on them in 1964 (6.25). By 1976 the DIVT 13 system began to be produced for the AMX-10 RC reconnaissance vehicle and a similar system was subsequently adopted for the AMX-30 tank.

The low light level television systems produced by Thomson-CSF use a 25mm diameter silicon intensified target and have an effective range of about 1000m under starlight conditions. This is comparable to the performance of multi-stage first-generation and of second-generation image intensifiers. At the same time low

light level television systems have the advantage over image intensifiers in being able to display the scene viewed on two or more monitors so that, for instance, the gunner and the commander of a tank can see it simultaneously. However, like the first-generation image intensifiers with cascade tubes, they are relatively bulky and they have not been widely adopted, except for tanks produced in France, including the AMX-40 prototype built in 1983.

6.6 Thermal Imaging Systems

Although image intensifiers and low light level television are superior, in general, to the earlier active infrared systems, they also have their limitations. In particular, their performance is very dependent on ambient light levels. It is also dependent on the target-to-background contrasts and on the meteorological conditions, which can restrict it severely, as do smoke and dust. Most of these limitations are shared by daylight vision devices but not by thermal imaging systems, which are superior therefore to image intensifiers and low light level television and which have been replacing them to a growing extent since the 1970s.

The superiority of thermal imaging over all earlier night vision systems stems from their basic feature, which is that they function by detecting the radiation naturally emitted by all warm objects, instead of the reflected infrared or visible radiation on which the other systems rely. The radiation it detects enables a thermal imager to establish the thermal pattern of a scene and this is then converted into a visible image, which is an analog of the thermal image, since the variations in the temperature of the scene tend to correspond to its visual details (6.26).

The quality of the image depends on the radiation contrasts and therefore on the difference between the temperature of the objects viewed and of the background. These differences are relatively small for most objects of military interest and at near ambient temperature the spectral distribution of their radiation peaks at a wavelength of about 10 microns. In consequence, thermal imagers are generally designed to operate at wavelengths of between 8 and 14 microns, at which most of the radiation occurs and when their sensitivity can therefore be highest. Moreover,

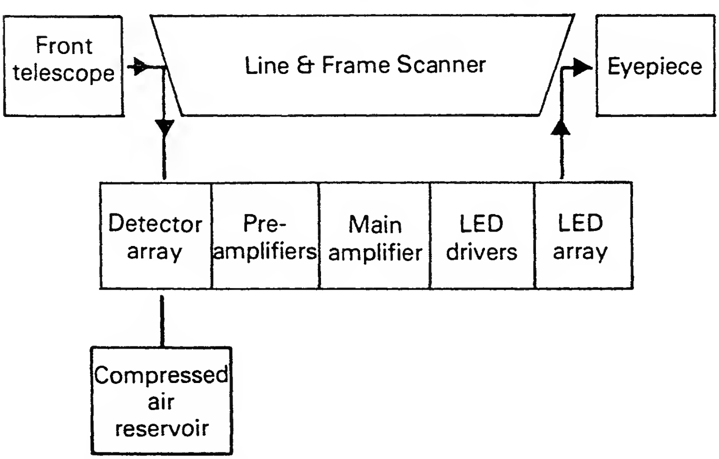


Fig. 6.6 Functional diagram of a thermal imager.

wavelengths of 8 to 14 microns coincide with one of the atmospheric 'windows', or wavelength regions in which the transmission of thermal radiation through the atmosphere is high. Because of this thermal imagers can detect objects at relatively long range. In fact, they can detect tanks at 3km and make it possible to recognise them at 2km.

The wavelengths at which they operate also make it possible for thermal imagers to detect objects through haze, dust and smoke, because the size of their droplets or particles is smaller. As a result, conventional smoke screens are ineffective when thermal imagers are used. However, their use has prompted the development of new types of smoke screens containing screening agents which reduce their effectiveness, as mentioned already in Chapter 5.

Fog, rain and snow also have an adverse effect on the performance of thermal imagers, because of the relatively large size of the droplets of the water which they contain. On the other hand, the temperature sensitivity of thermal imagers is 0.5°C, or even 0.1°C, and their ability to detect such very small differences in temperature enables them to detect targets when they are camouflaged by natural or artificial means. For the same reason they can even detect where mines were recently buried, because of the difference between the temperature of the earth which had been disturbed and of its immediate surroundings.

To sense the thermal radiation from targets thermal imagers contain cadmium-mercury-telluride detectors which have to be maintained at very low, cryogenic temperatures. In fact, they are cooled to about -200°C either by a miniature, closed-cycle, Stirling refrigerator or by the expansion of high pressure gas in a Joule-Thomson cryostat, the gas being supplied by high pressure bottles. To be cooled to such a low temperature the detectors must be mounted in a vacuum flask, or dewar.

First generation thermal imagers also need to incorporate an opto-mechanical scanner. This may consist of a mirror on a two-axis gimbal or of two mirrors oscillating or rotating about axes perpendicular to each other, which receive the radiation from the scene collected by suitable optics and, by reflecting it, sweep it vertically and horizontally across an array of detectors. In this way the scene is scanned in line and frame by the detectors, of which there has to be an array because their response time is too slow to permit a single detector to interrogate the scene at sufficiently high rates. Thus, several detectors are used to simultaneously scan the scene, typical two-dimensional arrays having 48, 60 or 120 detectors.

As they are swept by the radiation from the scene, the detectors generate analog electrical signals which are amplified, processed and used to drive a matching array of light emitting diodes. The light emitted by the diodes is projected on to the other side of the scanner mirror, which reflects it into a direct view eyepiece or into a vidicon for remote viewing with a cathode ray tube. Alternatively, detector outputs are multiplexed, or added serially and combined into one video signal to provide a cathode ray tube display.

A thermal imaging system is obviously more complex than any image intensifier and, inevitably, costs more to produce. It also presents installation problems because optical glass does not transmit radiation with wavelengths of 8 to 14 microns, which means that thermal imagers can not be integrated with normal daylight vision channels of tank sights. Instead, they have to be provided with separate channels with germanium optics. On the other hand the performance of thermal imagers is greatly superior to that of all earlier night vision devices and they are also effective in daylight for such purposes as the detection of targets

which are camouflaged or obscured by conventional smoke screens. They are also completely passive and independent of ambient light, being able to operate under conditions ranging from total darkness to bright sunlight, although they tend to produce better images at night when there is greater contrast between the radiation from the targets and the cooler background.

In some respects thermal imagers might be simplified and made more compact by the use of focal plane arrays or mosaics with high densities of detectors, which eliminate the need for opto-mechanical scanners, although they tend to increase the complexity of the electronics. However, such solid-state devices require much higher densities of detector elements than those used in the first generation of thermal imagers with opto-mechanical scanners to achieve an acceptable degree of image resolution. Thus, a typical focal plane array based on a platinum silicide hybrid chip comprises 65 536 infrared detectors in a mosaic with 256 detectors across and 256 detectors down, but thermal imagers based on such arrays are still in an early stage of their development.

In fact, it was only in 1977 that the first thermal imagers were produced by the Hughes Aircraft Company for installation in the US M1 tanks. These were, of course, first-generation imagers with opto-mechanical scanners and 120-element detector arrays. Prior to their adoption for the M1 tank thermal imaging systems had been used in aircraft. They were first used in action in 1967 in the 'gunships' used in Vietnam by the US Air Force for close air support but it took another five years for their cost to be reduced sufficiently for them to be considered for tanks.

6.7 References

6.1 J F C Fuller, *Tanks in the Great War*, John Murray, London, 1920, p.204.
6.2 B H Liddell Hart, *The Tanks*. Vol.I, Cassell, London, 1959, p.254.
6.3 J F C Fuller, *Armoured Warfare*, Eyre and Spottiswoode, London, 1943, p.144.
6.4 *Armored Force Field Manual*. FM 17-10, US Government Printing Office, Washington, 1942, p.134.
6.5 G le Q Martel, *An Outspoken Soldier*, Sifton Praed, London, 1949, p.55
6.6 J F C Fuller, *The Second World War*, Eyre and Spottiswoode, London, 1948.
6.7 N W Duncan, *79th Division*, Profile Publications, Windsor, 1972, p.6.
6.8 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, p.399.
6.9 J L Fellows, 'Tank Searchlights', *Armor*, Vol.63, No.1, January-February, 1954, pp.16-21.
6.10 W L Warnick and R A Baker, *The Tank Commander's Guide*, Stackpole, Harrisburg, 1963, p.471.
6.11 *Handbook on Weaponry*, Rheinmetall, Düsseldorf, 1982, pp.538-539.
6.12 R D Hudson, *Infrared System Engineering*, Wiley, New York, 1969.
6.13 R Lusar, *Waffen und Geheim-Waffen des 2. Weltkrieges und Ihre Weiterentwicklung*, Lehmanns, Munich, 1959.
6.14 P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978, pp.176-177.
6.15 S J Zaloga, *Modern Soviet Armour*, Arms and Armour Press, London, 1979, p.11.
6.16 M L Aitken, 'Cat's Eyes for Cannons', *Armor*, Vol.74, No.2, March-April 1965, pp.29-31.
6.17 W J Spielberger, *From Half-Track to Leopard 2* Bernard & Graefe, Munich, 1979, p.291.
6.18 C R Steward, 'Night Vision for Tanks', *Armor*, Vol.69, No.6, November-December, 1960, pp.6-8.

6.19 G R Elion and H A Elion, *Electro-Optics Handbook*, Marcel Dekker, New York, 1979.
6.20 W Kuhl, 'Night Vision - A Vital Aid to the Modern Army', *Armada International*, Vol.7, No.5, September-October, 1983, pp.140-154.
6.21 'Evolutionary Development of Image Intensifying Technology', *Armada International*, Vol.7, No.5, September-October, 1983, pp.156-163.
6.22 L A Wolcott, *Interoperability – The Answer to International Standardization of Combat Vehicles*, Technical Paper 780338, Society of Automotive Engineers, Warrendale, 1978.
6.23 *Integrated Small Craft Weapon Systems*, Delco Electronics, Santa Barbara, 1975.
6.24 *RCA Electro-Optics Handbook*, RCA, Lancaster, 1974.
6.25 J Dansac, C Pepin and G Mouneyrat, 'Low Light Level Television for Tanks', *2nd International Conference on Low Light Level and Thermal Imaging*, Institution of Electrical Engineers, London, 1979.
6.26 J M Lloyd, *Thermal Imaging Systems*, Plenum Press, New York, 1975.

Chapter 7

Fire Control Systems

7.1 Evolution of Fire Control Systems

To hit the targets at which they are fired, tank guns must have the axes of their barrels offset from the line of sight to the target by an amount dependent on a number of phenomena. The most important of these is gravity drop, that is the height through which a projectile falls during its time of flight. For a given projectile velocity, the height of the drop depends largely on the range of the target and has to be compensated for by elevating the gun above the line of sight. The angular difference between the latter and the axis of the gun barrel is called superelevation.

If the target is moving relative to the gun its position changes during the time of flight of the projectile and this must also be compensated for, by rotating the barrel of the gun ahead of the line of sight, so that it does not point in the direction of the target but where the target will be after a time equal to that required by the projectile to reach it. The required angular difference between the axis of the gun barrel and the line of sight is called the lead and for a given projectile velocity is governed by the velocity of the target.

At first the superelevation of tank guns was based on visual estimates of the range of targets and on gunners selecting the corresponding mark on the range scale which formed part of the graticule of their telescopic sights. Such a range scale was already part of the graticule of the telescopic sight used with the 37mm gun of the Renault FT light tank of 1918 (7.1). Sights with similar scales have continued to be used to this day in many of the less sophisticated armoured vehicles. Alternatively, as in the Vickers Medium tanks of the 1920s, the sighting telescope only had cross wires and superelevation was set by the gunner rotating the telescope in relation to the bore of the gun by means of a range drum. Similarly, moving targets have been engaged with the gunners estimating the necessary aim-off or, in other words, how far ahead of the target to aim.

Gun laying of this kind, which relies on the skill of the gunners, has worked reasonably well with trained gunners and at relatively short ranges. But as the range of engagements increased during the Second World War visual range estimation became increasingly unsatisfactory and this led to the adoption in tanks of optical rangefinders.

The first tank for which an optical rangefinder was adopted appears to have been the final version of the German Panther, which was developed in 1945 but which never advanced beyond prototypes (7.2). Further progress in the use of optical rangefinders was made soon after the Second World War when they were

adopted for the then newly designed US T37 light, T42 medium and T43 heavy tanks. The T42 led to the M47 medium tank which, in 1952, became the first tank to go into service with an optical rangefinder. Optical rangefinders were also mounted in the next US medium tank, the M48, and its successor, the M60, and they were also fitted in most tanks designed outside the Soviet Union during the 1950s. These tanks included the German Leopard 1, the French AMX-30, the Swiss Pz.61 and the Japanese Type 61, as well as the British Conqueror.

No Soviet tank was fitted with an optical rangefinder until the introduction of the T-64 in the 1970s. In the meantime T-54, T-55 and T-62 relied on the far less accurate stadiametric method of ranging. Nor were British tanks fitted with optical rangefinders except for the Conqueror. Instead, the late models of the Centurion and the original versions of the Chieftain were fitted with ranging machine guns.

During the 1960s the earlier methods of ranging began to be superseded by the use of laser rangefinders which represented a major advance in accuracy on all of them. In consequence, starting with the US-German MBT-70, tanks designed since the mid-1960s have not been fitted with any other means of ranging and in the early 1970s laser rangefinders began to be retrofitted in tanks originally built with other ranging devices.

In several cases laser rangefinders were used by themselves, like some of the optical rangefinders, which left it to the gunners to read what range they registered and then pick the corresponding mark on the range scales of the graticules. This was the case with the Tank Laser Sight produced by Barr & Stroud for the Chieftain and with the CILAS TCV 29 rangefinder mounted on the Steyr Kürassier, as well as other vehicles.

However, the development of lasers was accompanied by the appearance of electronic computers which could be used to position an aiming mark injected into the gunner's sight correctly and directly from the output of the rangefinder. This made it possible to replace the complex graticules, with a different scale for each of several types of ammunition, by a simple aiming mark, which reduced the chances of error by the gunner. Moreover, given a suitable, powered drive the electronic computer could also be made to control the elevation of the gun and thus to give it the correct superelevation, bringing the aiming mark back on to the target and

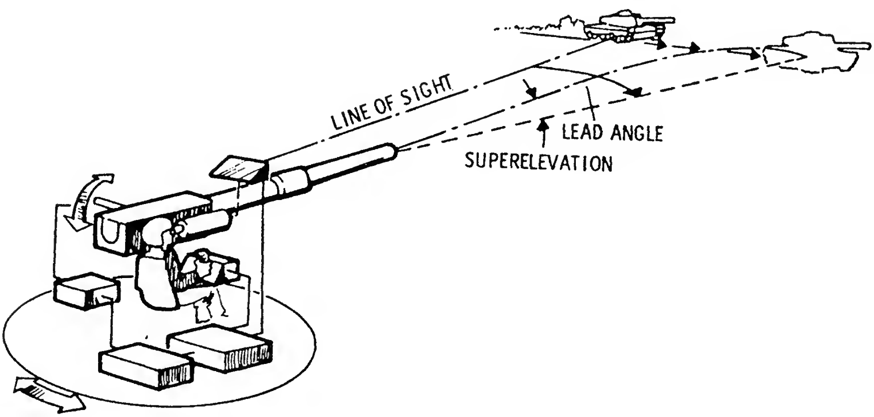


Fig. 7.1 Diagram illustrating the basic aspects of aiming a tank gun.

absolving the gunner of the need to do so, except perhaps for a small final correction.

A similar result had been achieved with the optical rangefinders of tanks such as the US M47 in which, as the gunner ranges, the superelevation appropriate for the type of ammunition to be used is automatically applied to the gun. Much the same happened with the gunner-operated optical rangefinder of the German Leopard 1 but in the US M48 and M60 tanks, in which the optical rangefinder has been operated by the commander, the method used has been somewhat different. In the M48A2, for instance, data from the rangefinder has been transmitted mechanically, by a rotating shaft, to a ballistic computer which then applied the appropriate offset through a ballistic drive to the gunner's sight, and also to the rangefinder, while the gunner elevated the gun to keep the aiming cross of his sight on the target. To cope with as many as six different types of ammunition, the M13A1 ballistic computer contains the same number of suitably shaped cams, which are selected manually by the gunner according to the ammunition used. Two cams are also incorporated in the rangefinder of Leopard 1 for the same purpose.

The adoption of electronic computers in combination with laser rangefinders in place of optical rangefinders and mechanical computers made it possible to determine the range, and hence the superelevation, much more accurately and quickly and, in addition, to take into account several other factors involved in gun laying. One of them is the lead angle required to engage a moving target, which can be determined by electronic computers from measurements of the angular rate of movement of the turret when the target is being tracked. The problem of target motion had already been tackled elsewhere and especially in connection with aerial gunnery (7.3). The outcome of it was the introduction during the latter part of the Second World War of the Ferranti lead-computing gyroscopic gun sights on British fighter aircraft, even though the only method that could be used in them to determine the range of targets was stadiametric (7.4). Gyroscopic as well as other lead-computing sights have also been developed for anti-aircraft guns (7.5). However, the slower speeds of ground targets made their motion less important in tank gunnery. Thus, until the advent of electronic computers, aim-off was left to be estimated by tank gunners.

Other factors taken into account by electronic computers in calculating the offsets between sights and guns include trunnion tilt or cant, ambient temperature and pressure, wind velocity, propellant temperature and bore wear. All these factors can be taken into account automatically by means of appropriate sensors linked to the computer, although with different degrees of accuracy. Alternatively, they can be introduced manually, by switches on a control panel, and to some degree manual inputs have been relied upon in most systems.

The one factor which has not been introduced manually is trunnion tilt, that is the angle between the axis of the gun trunnions and the horizontal. It occurs when a tank is not on level ground and changes the geometrical relationship between the sight, the gun and the ground, for which corrections have to be made if significant errors are to be avoided, particularly in azimuth. This requires measurement of the tilt angle, which has been done automatically with a magnetically damped pendulum or a highly damped linear accelerometer oriented to measure the tilt angle as a deviation from the vertical. However, neither of the two types of static tilt sensors has proved satisfactory when tanks are moving and they are commonly switched off for firing on the move.

Ambient temperature and atmospheric pressure are significant because they effect air density and, consequently, drag and hence the trajectory of projectiles.

They can be measured by resistance thermometers and pressure transducers whose output can be fed automatically into the computer but as they do not have to be monitored continuously they are entered manually in several systems.

Crosswind and headwind velocity data can also be fed automatically from sensors such as hot wire anemometers but headwind is not generally considered to have an important effect on the trajectory of tank gun projectiles, so that measurements are usually confined to crosswind velocities. However, wind velocities measured at the tank are not necessarily the same as those down range and since wind sensors have to be mounted on tops of tank turrets they are vulnerable to damage. As a result, the use of wind sensors has been widely questioned and often rejected, crosswind data being entered manually, if required.

The best that can be done about propellant temperature,which affects muzzle velocity, is to measure the temperature in the ammunition storage area and this can be entered either automatically or manually. Barrel wear also affects muzzle velocity and since it is a function of the number of rounds fired from a gun it can, in principle, be determined by counting how many rounds have been fired. Counters have therefore been installed for this purpose but a correlation between the number of rounds fired and barrel wear has proved difficult to establish and in most cases corrections for wear have been entered manually.

Provision for manual inputs is generally made even where the inputs are normally automatic to ensure an alternative, fall-back mode of operation in the event of failure of any of the automatic sensors. Manual inputs are also required to identify the type of ammunition being fired and they are provided by a selector switch operated by the commander or the gunner.

The ballistic computers for which all these inputs have been provided were originally of the analog as well as of the digital type. Thus, a digital computer was incorporated in the fire control system developed in the mid-1960s by Delco Electronics for the MBT-70, the first tank to be built with a 'full solution' fire control system with an electronic computer. But the system developed by Delco Electronics in the early 1970s for the General Motors XM-1 prototype incorporated an analog computer, which was chosen partly because it was less expensive.

Similarly, the Cobelda fire control system developed between 1966 and 1969 by SABCA for the Leopard 1 tanks of the Belgian Army incorporated an analog computer designed by the Hughes Aircraft Company (7.6, 7.7). Another analog computer was also adopted for the fire control system developed in the early 1970s for retrofitting US M60A1 tanks and eventually produced for the M60A3 as the M21 computer. The FLT 2 fire control system produced for the Leopard 2 by Krupp Atlas Elektronik in collaboration with the Hughes Aircraft Company also incorporates an analog computer.

On the other hand, the system developed by General Dynamics for the US M1 tank incorporates a digital computer, produced by Control Data Corporation. So do other recently developed fire control systems. They include the Improved Fire Control System, or IFCS, developed by Marconi Command and Control Systems for the British Chieftain tanks and even the relatively simple SFCS 600 developed by Marconi and fitted in the Mark 3 tanks produced by Vickers Defence Systems for Kenya and for Nigeria.

The use of digital computers in preference to the analog type is due to their greater flexibility, which means that they can be easily programmed for several different types of ammunition and in addition to ballistic calculations used for several other purposes. The heart of a digital computer is a microprocessor, which

typically has come to be of the 16-bit type so that it can perform calculations rapidly and accurately. A typical computer is designed to accept up to 32×10^3 bytes of programmable read-only memory, although less than 10^4 bytes are needed to provide a full ballistic solution for fire on the move.

The development of fire control systems incorporating electronic computers and laser rangefinders as well as various sensors has increased considerably the ability of tank guns to hit targets. This, among other things, strengthened the position of guns as the main armament of tanks in face of competition from guided missile systems. However, the practical value of fire control systems has varied considerably with the type of ammunition and the circumstances. For instance, it has been relatively low with guns firing high velocity projectiles such as APFSDS from stationary tanks at targets located at the relatively short ranges at which they are most frequently found. In this case the flat trajectory of the projectiles and their short time of flight make them relatively insensitive to ranging errors and environmental factors. At longer ranges the benefits of the fire control system are much greater, particularly with the lower velocity HEAT and, even more, HESH projectiles. The benefits are greater still when the targets are moving. However, assessments of the benefits of fire control systems against moving targets have been based, in general, on crossing targets, that is on targets moving at right angles to the firing tanks. This does not represent a situation that is of prime importance on the battlefield, where targets approaching head-on or moving at small angle to the line of sight of the tank are much more important.

7.2 Ballistic and Stadiametric Rangefinding

Of all the various developments which have contributed to increasing the hit probability of tank guns the most important has been progressive improvement in the methods of determining the range of targets. The original method of doing it by visual range estimation has been generally very inaccurate, the errors produced by it having a standard deviation equal to 25 to 30 per cent of the range. Intensive training can reduce the standard deviation of the ranging errors somewhat but, in general, not below 20 per cent of the range. In consequence, when gunners have to rely on visual range estimation the probability of hitting targets with the first shot is not very high, unless the targets happen to be at short ranges.

If no other means of determining the range are available, a high chance of hitting a target can only be obtained by firing two or more rounds using what is known as the burst-on-target method. This involves observing where the first round appears in the sight in relation to the target and relaying the gun on that spot before firing the second round (7.8). Alternatively, two or more rounds may be fired at different range settings to bracket the target and thereby to arrive at the correct setting for hitting it. In either case rounds have to be fired initially for what are, in effect, ranging purposes, which is obviously wasteful of ammunition. Nevertheless, the use of gun ammunition for ballistic ranging may have been practicable during the Second World War or even later when tanks still carried 60 rounds or more. But it became increasingly impracticable as the calibre of tank guns rose further, to 120 or 125mm, and the number of rounds that tanks could carry decreased to 40 or less. Moreover, even if main armament rounds could be expended for ranging, the obscuration which the firing of large calibre guns produces is such that the flight of the projectiles can not be observed by the gunners.

In the meantime a much more economical method of ballistic ranging was adopted for the British Centurion and Chieftain tanks. It involved the use of a

modified 12.7mm machine gun to find the range by firing short bursts aimed by laying on the target successive dots or marks on the range scale for the machine gun in the graticule of the sight and then observing which burst hits the target and, therefore, which mark gives the correct range. The gunner then picks the corresponding mark on the range scale appropriate to the type of gun ammunition which is to be fired and lays it on the target. Alternatively, he may use the same mark if the range scale of the machine gun and of a particular type of gun ammunition happen to be the same, which has been the case with the HESH ammunition of the Chieftain's 120mm gun.

The use of a machine gun for ranging is obviously far less demanding of the volume of the ammunition carried in a tank than the use of the main armament for the same purpose. At the same time it enables the range of the target to be determined with a reasonably high degree of accuracy, the standard deviation of ranging errors being about 50m at 1000m. Its use also has the advantage of taking into account trunnion tilt and crosswind. However, the ranges to which it can be used are inevitably limited by the performance of the machine gun ammunition. In the case of the Centurions the maximum range to which the ranging machine gun could be used was actually 1800m. In the case of the Chieftain the maximum range was extended to more than 2000m but, nevertheless, machine guns can not be used when ranges are long and when range information is needed most. The use of ranging machine guns does not produce any of the obscuration associated with the firing of tank guns but it is not entirely unobtrusive and can therefore disclose the position of a tank prematurely. It was also found that, although the ranging machine gun system was basically simple and robust it took more time to engage successive targets with it than with the contemporary fire control system of Leopard 1 which was based on an optical rangefinder.

All this and the development of other, more accurate means of determining the range of targets confined the use of ranging machine guns to only three major types of tanks. The first of them was the Centurion, the improved 105mm gun versions of which began to use ranging machine guns in 1962. By then the 12.7mm ranging machine gun had also been adopted for the Chieftain, which was produced with it until the mid-1970s. The third tank was the Vijayanta designed by Vickers and produced in India from 1965 onwards. In 1959 the 12.7mm ranging machine gun was also adopted for some of the prototypes of Leopard 1 but only to be abandoned after trials in 1962 (7.9). It was also considered for the Swedish S-tank but again it was abandoned before that tank began to be produced in 1967 (7.10).

Apart from using special ranging machine guns, tanks can also range ballistically with their coaxial machine guns. But this is of practical value only when they are armed with low-velocity guns, such as the 76mm L23 of the British Scorpion light tank. When they are armed with high velocity guns there is little to be gained by ranging with 7.62mm or similar rifle-calibre coaxial machine guns because of the relatively short effective range of their tracer bullets.

Another method of determining the range of targets which has been generally available and which does not suffer from the limitations of ballistic range-finding with coaxial machine guns is stadiametric rangefinding with hand-held binoculars or 'field glasses'. This requires knowledge of the height or width of the target and a graticule in the binoculars with scales, graduated in mils, by means of which the angle subtended by the height or the width can be measured, in order to obtain the range from the quotient of their dimension and the angle. The same method can also be used with tank sights, provided they have graticules with suitably graduated scales, and it was a recognised way of finding the range of ship targets with

submarine periscopes when tanks had hardly begun to be developed (7.11).

For any one type of target the need to divide either of its dimensions by the angle which it subtends can be eliminated by incorporating in the graticule a pattern of two horizontal or vertical curves separated so that the varying distance between them corresponds to the apparent height or width of the target at different distances, marked along the curves. The range of the target can then be simply obtained by superimposing on it the pattern of the two curves so that they just bracket it and then reading the corresponding range mark.

Such a stadia pattern has been incorporated in the TPK-1 commander's sights installed in Soviet T-54 and T-55 tanks as well as in their TSh 2-22 gunner's sights. In this case the stadia pattern is horizontal and corresponds to a target height of 2.7m, which is approximately the height to the turret roof of tanks such as the US M48 and M60.

Apart from Soviet tanks few others have had a stadia pattern in the graticules of their sights. One of the few has been the Leopard 1, which has had it in the TRP 2A panoramic commander's periscope. Two others have been the US M551 Sheridan and the M60A2, both of which have had vertical stadia patterns in the gunner's periscope for ranging when firing conventional ammunition from their 152mm gun-launchers.

In view of its simple nature, the accuracy of the stadiametric range finding can not be very high. In fact, the standard deviation of the ranging errors produced by it has been of the order of 15 to 20 per cent of the range. This may be high by other standards but it represents significantly smaller errors than those associated with visual range estimation. There has been a strong case therefore for having stadia patterns in the sights of tanks which can not be provided with more sophisticated means of range-finding, and even in other tanks as a supplementary or emergency

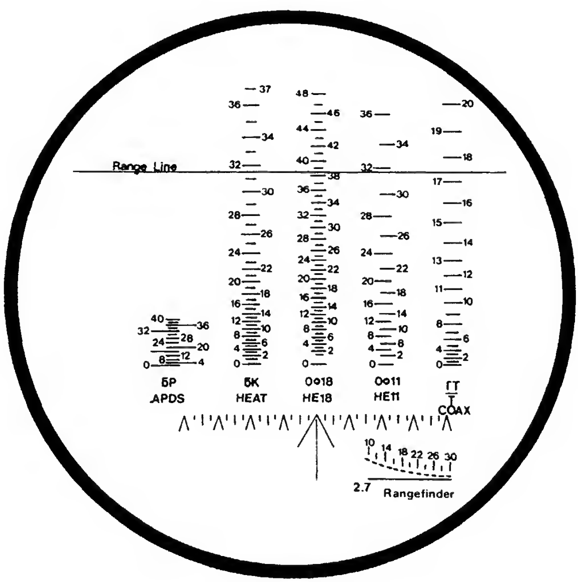


Fig. 7.2 Graticule of the gunner's sight of the Soviet T-62 tank with range scales for the different types of ammunition and a stadia pattern in the bottom right. (US Army)

means of determining the range of targets, particularly in view of the negligible cost of adding them to the graticules.

7.3 Optical Rangefinders

Although a sight with a graticule incorporating a stadia pattern may be described as an optical rangefinder, this description is generally reserved for optical instruments which are designed specifically to determine the range of targets. These instruments had been developed well before the first tanks were built during the First World War and they had become important during that conflict, particularly in warships. But there was no incentive to use them in tanks until the latter part of the Second World War, when the growth in the size of tank guns extended considerably the range of engagements.

When optical rangefinders were eventually installed in tanks they were either of the coincidence or of the stereoscopic type. In essence, both types consist of two telescopes mounted in a common frame and in either case the range is obtained from the measurement of the angle subtended at the target by the optical base of the rangefinder, that is the distance between its two objectives. In consequence, the accuracy of both types of rangefinders is proportional to the length of the base. However, they differ in other respects and in particular in the method by which the range is actually determined.

In the case of the coincidence rangefinders, which were pioneered in Britain by Barr & Stroud, the range is determined in two different ways. One amounts to adjusting the images of the target obtained from the two ends of the optical base until they overlap each other completely, this being known as the superposition method. The other method involves splitting of the field of view and the alignment of the images of its two parts.

Stereoscopic rangefinders, which were originally developed in Germany by Zeiss, depend for their operation on the perception of depth associated with binocular vision. One way of exploiting it has been to incorporate a fixed mark in the focal plane of one eyepiece and a moving mark in the other with which the operator brackets the target and then adjusts the moving mark until it is at the same apparent range as the target. Of the two stereoscopic rangefinders have been the more difficult to use and only a relatively small number of men have been capable of using them effectively. This was realised during the First World War or even earlier (7.12, 7.13). However, what was known at that time was forgotten, or ignored, after the Second World War when the US Army decided to adopt stereoscopic rangefinders for its tanks and in particular for the M47 medium tank. The inevitable outcome of it was that after the M47 was introduced into service in 1952 there was considerable dissatisfaction with its M12 stereoscopic rangefinder in US armoured units (7.14, 7.15). Nevertheless, a similar rangefinder was adopted for the M103 heavy tank. What is more, the M48, which followed the M47 as the principal tank of the US Army, was also produced with a stereoscopic rangefinder, the M13. But the next tank, the M60, which was adopted in 1959, was produced with the M17 full-field, superposition type, coincidence rangefinder, which was simpler to operate and required much less training (7.16). A similar rangefinder was also installed in the late versions of the M48, the M48A3 and M48A5.

The M12 rangefinder of the M47 had a base of 1.52m and was operated by the gunner. On the other hand, the M13 and M17 rangefinders had a longer base length of 2.0m, which increased their accuracy but made it necessary to mount

them farther back in the turret and to be operated by the commander. This change was supported by arguments that traditionally tank commanders determined and announced the range but it represented a retrograde step in taking the attention of the tank commanders away from their principal task of tactical command of tanks.

A similar distraction was avoided in the design of Leopard 1, which in its original version incorporates a rangefinder operated by the gunner. The Zeiss-made TEM 2A rangefinder has a base length of 1.72m and, true to the traditions of the German Navy in the First World War, is of the stereoscopic type but it can also be operated in coincidence mode. Apart from its use for rangefinding, the TEM 2A is also used for target acquisition and in this case the wide separation of its objectives produces an effect equivalent to increasing the inter-ocular distance. This enhances stereoscopic vision and, therefore, depth perception, which helps in the detection of camouflaged targets (7.17). The binocular vision provided by a stereoscopic rangefinder like the TEM 2A also makes it possible to use it under poorer light conditions than those under which coincidence rangefinders can be used, since the latter are monocular.

In contrast to Leopard 1, the AMX-30, which was designed to the same Franco-German set of requirements, has had a rangefinder operated by the commander. Its M208 coincidence rangefinder made by SOPELEM is of the full-field superposition type and has a base length of 2.0m. Similarly, the Swiss Pz.61 and Pz.68 have had coincidence rangefinders but of the split-image type and operated by their commanders. They were made in Switzerland by Wild AG and have a base length of 1.55m.

In the British Conqueror heavy tank and in the Japanese Type 61 the policy of allocating the rangefinder to the commander was implemented in its extreme form by mounting it in the commander's rotating cupola, even though this restricted its base length and therefore its accuracy. Thus, the split image coincidence rangefinder of the Conqueror had a base length of 1.25m while that of the Type 61 has had a base length of only 1.0m.

In addition to being dependent on the base length, the accuracy of the optical rangefinders also depends on the range of the targets. In fact, the errors in the range determined with them increase with the square of the distance, which was recognised even before the First World War (7.18). This means that they are significantly less accurate when the ranges are long, which is when range information is most important. However, the actual value in metres of the standard deviation of the ranging errors has been of the order of 10 to 20 times the square of the range in kilometres, and this represents significantly smaller errors than those associated with all the other methods of ranging described so far.

Unfortunately, to achieve their relatively high accuracy optical rangefinders had to have long base lengths, which meant that they took up a considerable amount of space within tank turrets and were difficult to install without adverse effects either on turret shape or on the division of duties between commanders and gunners. To overcome these problems and to increase accuracy still further Leitz developed an optical rangefinder with electro-optical correlation of the images which had a base length of only 350mm. This rangefinder was installed in 1973 in one of the prototypes of Leopard 2 but it was not adopted for the production version of that tank which was fitted instead with a laser rangefinder (7.19).

7.4 Laser Rangefinders

At the time optical rangefinders began to be used in tanks work had also started on new types of electro-optical rangefinders. These were based on the measurement of the time of transit of pulses of light from the rangefinder to the target and back again and they were to prove much more accurate than optical rangefinders.

The first major attempt to use an electro-optical rangefinder was represented by the T53 Optical Tracking, Acquisition and Ranging (OPTAR) system, which was tested on the US T95 tank between 1955 and 1957 (7.20). This system emitted pulsed beams of light which was incoherent and, consequently, had a tendency to scatter, resulting in multiple returns. It was necessary therefore for its users to decide which of the returns was correct by visually estimating the range. In addition, the transmitter and receiver assembly of the OPTAR system was relatively large and vulnerable. As a result, the OPTAR system was abandoned.

No other attempt appears to have been made to develop electro-optical rangefinders until the advent of lasers which, unlike normal light sources, emit light that is coherent. In consequence, laser beams can be narrowly focused and this made them very suitable for ranging as well as other purposes.

Lasers take their name from the initials of Light Amplification by Stimulated Emission of Radiation, which describes their basic function. The first came into being in 1960 at the Hughes Research Laboratories in California, where T H Maiman discovered a material capable of amplifying light when suitably excited and the means of exciting it (7.21). This led to an experimental laser rangefinder called Colidar, which the Hughes Aircraft Company developed by the end of 1962, and it soon became evident that laser rangefinders would provide tanks with a new and superior means of ranging (7.22). In fact, Hughes Aircraft Company supplied in 1964 a laser rangefinder for trials in a German Leopard 1 and a year or two later

Fig. 7.3 US T95 tank with the OPTAR electro-optical system which preceded the development of laser rangefinders. (US Army)

in the Swedish S-tank, Swiss Pz.61 and Japanese Type 61. Moreover, a laser rangefinder made by the Radio Corporation of America was incorporated in the design of the US-German MBT-70. which was built in 1967, and in 1969 Hughes Aircraft Company received the first production order for laser rangefinders for the US M60A2 tank, of which 300 were built by 1970.

All the early rangefinders, including those produced in the early 1970s by Hughes Aircraft Company for the US M551 Sheridan and under licence from Hughes by Barr & Stroud for the British Chieftain tanks, used a pink ruby crystal as the laser material. The ruby is made from alumina (Al_2O_3) mixed with chromium oxide (Cr_2O_3) and usually takes the form of a cylindrical rod. It is excited by optically pumping energy into it by means of a flashlamp. The excitation is built up to increase the intensity of the light pulses by controlling their emission by what is known as Q-switching, which commonly involves the use of a rotating prism or mirror at one end of the ruby rod (7.23).

The ruby laser rangefinders made it possible to determine ranges of up to 10km with an accuracy as high as ± 10m. or even ± 5m. However, the radiation of the pink ruby has a wavelength of 0.69 micron, which is close enough to the visible part of the spectrum for the beams of ruby rangefinders to be seen with the naked eye under some conditions, particularly at night. Moreover, the early laser rangefinders emitted relatively wide beams with a divergence of about 1 milliradian. This resulted in range returns not only from the target but also from other objects and required the users of the rangefinders to discriminate between false and correct range readings. The high frequency with which false returns occurred with some of the laser rangefinders undermined confidence in them, which manifested itself clearly in 1974 when one was adopted for the Leopard 2 AV but only to be backed by a stereoscopic rangefinder, instead of being used by itself.

The beam divergence of some of the later ruby rangefinders, such as that incorporated in Barr & Stroud's Tank Laser Sight No.1 Mark II, was reduced to 0.5 milliradian. which is about the maximum it can be if false returns are to be minimised. Nevertheless, in the early 1970s ruby lasers began to be displaced by two other types of solid-state lasers.

The earlier of the two were lasers made of optical glass rods doped with neodymium. They are excited in a similar way to ruby lasers by optical pumping and they are also Q-switched mechanically, by means of rotating prisms. The early neodymium glass lasers also had a beam divergence of 1 milliradian but this was soon reduced to 0.5 milliradian or less, and they have an accuracy of at least ± 10m at up to 10km, with ± 5m being quoted for many of them. Moreover, neodymium glass lasers are considerably more efficient than ruby lasers and therefore consume less power (7.24). Because their radiation has a longer wavelength of 1.06 micron, the performance of neodymium glass lasers is degraded to a somewhat lesser extent by adverse weather conditions and for the same reason their beams can not be detected by eye.

Some of the early neodymium glass rangefinders had their transmitters and receivers mounted externally on gun mantlets or on turret roofs, which showed how simply they can be added to existing vehicles, albeit at the cost of becoming somewhat more vulnerable. An example of this is the TCV 29 rangefinder produced in France by the Compagnie Industrielle des Lasers (CILAS) and mounted on the turret of the SK 105 Kürassier built in Austria by Steyr-Daimler-Puch. However, more recent neodymium glass lasers have been integrated with the gunner's sights. This is exemplified by the Cotac M581 telescopic gunner's sight

developed in France by AMX-APX for the AMX-30 B2, which incorporates an APX M550/TCV 80 neodymium glass laser made by CILAS.

Neodymium glass lasers developed in Norway by Simrad have also been incorporated in rangefinders produced in Britain by Avimo but elsewhere ruby lasers have been followed by neodymium-YAG lasers. In general, the neodymium-YAG, or Nd-YAG, lasers are similar to neodymium glass lasers and their radiation has the same wavelength of 1.06 micron. But they can produce pulses at higher rates than neodymium glass lasers, which are handicapped by the low thermal conductivity of glass, and they can be even more compact and more efficient.

The Nd-YAG laser rods are made from single crystals of yttrium aluminum garnate ($Y_3Al_5O_{12}$) doped with neodymium. Like the others, Nd-YAG lasers can be Q-switched mechanically but, in general, two other techniques have been adopted for them. One involves the use of Pockels cell, of a crystalline material such as lithium niobate ($LiNbO_3$), which acts as an electro-optical shutter. The Pockel-cell Q-switch does away with the rotating components of the mechanical techniques and is more efficient but is also more expensive. The other Q-switch technique is based on a complex organic dye encapsulated in a plastic which blocks the emission of pulses until the excitation in the laser rod has built up to the desired level and then instantly and reversibly bleaches allowing a pulse to be emitted.

The passive, saturable dye form of Q-switching is evidently the least complicated and also the least expensive (7.25). In consequence, it has been widely adopted in preference to other forms of Q-switching since it was introduced in the mid-1970s. The earliest notable example of its use are the Nd-YAG lasers of the US M1 tank and of the German Leopard 2.

Neodymium lasers of both kinds have come to be integrated into the gunner's sights to the extent of sharing optics with the normal daylight vision channels, which makes for compactness, economy and precise, stable alignment of the lasers with the sights. All this has been made possible by the 1.06 micron wavelength of the neodymium lasers, which is close enough to the visible part of the spectrum for them to be compatible with visual optics. However, for the same reason neodymium lasers are an eye hazard, as are ruby lasers. This imposes severe restrictions on their use, particularly in peacetime training, and has led to increasing interest in lasers with wavelengths of more than 1.4 micron, at which the eye safe region of laser radiation is considered to begin (7.26).

The favoured alternative to neodymium lasers are carbon dioxide or CO_2 lasers. These gas lasers have a wavelength of 10.6 microns, which recommends them in

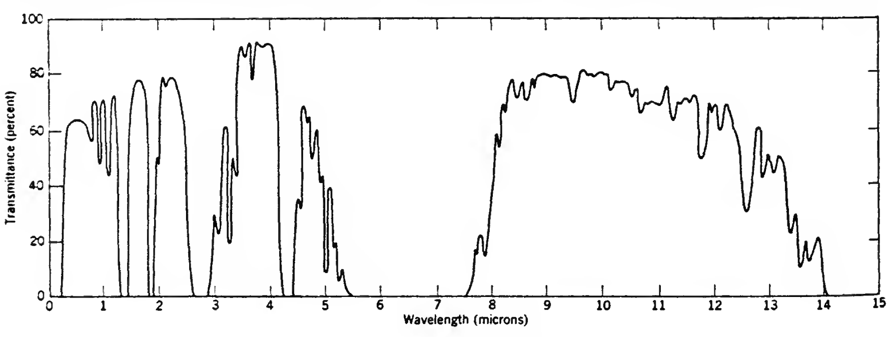


Fig. 7.4 Transmission of electromagnetic radiation through the atmosphere.

the first instance because it makes them operate within a wavelength 'window' in which transmission through the atmosphere is high, just as ruby and neodymium lasers operate in another window of high atmospheric transmission. The CO_2 lasers are also eye-safe, because radiation with a wavelength of 10.6 microns is not focused by the eye onto the retina and the energy output of the rangefinder laser is not high enough to damage the cornea by heating. Moreover, the wavelength of 10.6 microns makes CO_2 lasers compatible with thermal imaging systems, which operate at wavelengths of the same order. In consequence, they can use the same germanium optics and they share the advantage of being unaffected to a large extent by the smoke and dust which adversely affect human vision and neodymium lasers. This is due to the fact that the size of most smoke and dust particles is generally less than 2 microns. However, CO_2 lasers are not much better than neodymium lasers under conditions of high humidity, when large particles of water are present in the atmosphere, and for similar reasons they have difficulty in penetrating heavy rain and snow (7.27).

What is more, even when CO_2 lasers are not adversely affected by the weather, their ability to penetrate smoke and dust is only of value when they are used in combination with thermal imaging sights, as there is obviously no merit in being able to range when the target can not be seen. Thus, in the absence of thermal imaging sights CO_2 lasers offer little advantage over neodymium lasers, whose performance is entirely consistent with that of conventional, visual optics. On the other hand, when used in combination with thermal imaging sights, CO_2 lasers are liable to be adversely affected by the new types of artificial smokes with infrared screening agents which are being developed in response to the use of thermal imaging sights.

Carbon dioxide lasers have also been more expensive than neodymium lasers but this has been due, in part at least, to their more recent and, therefore, shorter development. In fact, the first CO_2 laser rangefinders were only fitted in the High Survivability Test Vehicle – Lightweight (HSTV-L), built in 1979 as part of the US Armored Combat Vehicle Technology Program, and then in experimental versions of the US M1 tank (7.28).

The accuracy of CO_2 rangefinders is generally stated to be $\pm$ 5m at up to 10km, but trials carried out with a Marconi Avionics rangefinder have shown an even greater accuracy of $\pm$ 3m at ranges of up to 4km (7.29). As with other laser rangefinders, statements about the CO_2 type do not, in general, define the ranging errors but they appear to involve either the mean or the standard deviation. In any case, a standard deviation of 5m is often taken to be representative of all laser rangefinders and shows them to be considerably more accurate than all earlier methods of ranging.

Carbon dioxide lasers differ from other, solid-state lasers in not employing Q-switching, those used being of the transverse excited, atmospheric pressure, or TEA, type. Like the solid-state lasers, some, including that mounted in the M1 tank, are of the pulsed type but others are continuous wave, or CW, lasers. The latter have the advantage over pulsed lasers in emitting less energy and of being able to provide information about the velocity as well as the range of targets. CW lasers are also suitable for other purposes, such as direct fire simulation in training, for which separate, low-powered gallium arsenide lasers have had to be used. However, continuous wave lasers are more complex and cost more.

7.5 Hit Probability

The effect which the development of rangefinders and of the other components of fire control systems has had on the probability of tank guns hitting their targets is illustrated in Fig. 7.5. This shows curves of single shot hit probability attainable with a typical 105mm tank gun firing APDS projectiles at a standard NATO 2.3m x 2.3m stationary target with the aid of different fire control systems. These range from a combination of a simple sight with a ballistic graticule and visual range estimation to a theoretically perfect fire control system. The progressive improvements in the hit probability which have been achieved are obviously considerable.

The improvements have varied, of course, with the type of ammunition. Thus, the greatest have been with low-velocity ammunition such as HESH, and the lowest with high-velocity APFSDS ammunition, as was indicated earlier.

Hit probability can be expressed in mathematical terms by assuming that when a gun is fired the vertical and horizontal locations of the impact points of its projectiles in the plane of the target follow a normal, Gaussian, distribution, as well as being independent of each other. In consequence, each distribution of impact points can be related to the centre of the target by a probability density function, which represents their relative frequencies and which, when integrated over the height or width of the target, gives the probability of a hit in elevation P_E or in azimuth P_A, respectively. Thus,

$$P_E = \frac{1}{\sigma_y \sqrt{2\pi}} \int_{-h/2}^{+h/2} e^{-0.5\left(\frac{y - ym}{\sigma y}\right)^2} dy \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 7.1$$

where y is the vertical distance from the centre of the target and h is its height. Of the two parameters which characterise the distribution, y_m is the arithmetic mean of the vertical distances from the impact points to the centre of the target. It represents, therefore, the displacement of the centre of the distribution in relation to that of the target, or the bias of the distribution. The other parameter, σ_y, is the standard deviation of the vertical errors, that is the root mean square of the deviations of the impact points from their arithmetic mean, which is a measure of their dispersion, or the spread of the errors.

A similar equation and comments apply to the probability of a hit in azimuth P_A. Since the errors in elevation and azimuth are mutually independent, the two hit probabilities can be multiplied by each other to give the probability of hitting the target P_H, i.e.

$$P_H = P_E \times P_A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 7.2$$

If necessary, the above approach to hit probability can be extended to targets which do not consist of a single rectangle. For instance, a tank target may be represented by two rectangles, corresponding to the turret and the hull, each of which can be dealt with as before and the probability of hitting the target is then obtained from the sum of the probabilities of hitting either one or the other of the two rectangles.

The integral of equation 7.1 can not be evaluated as a simple function of y and it is necessary therefore to integrate it numerically. This can be done in terms of the

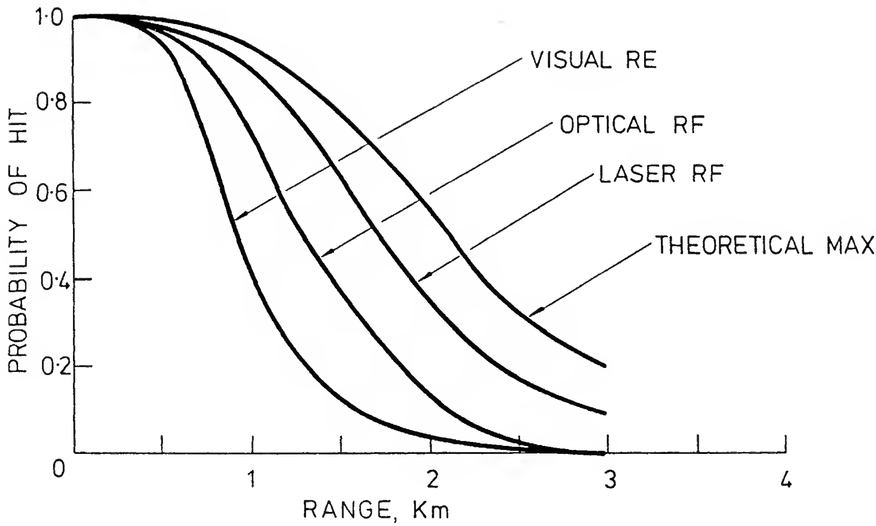


Fig. 7.5 Single shot hit probability attainable with a typical 105mm tank gun firing APDS with the aid of different fire control systems.

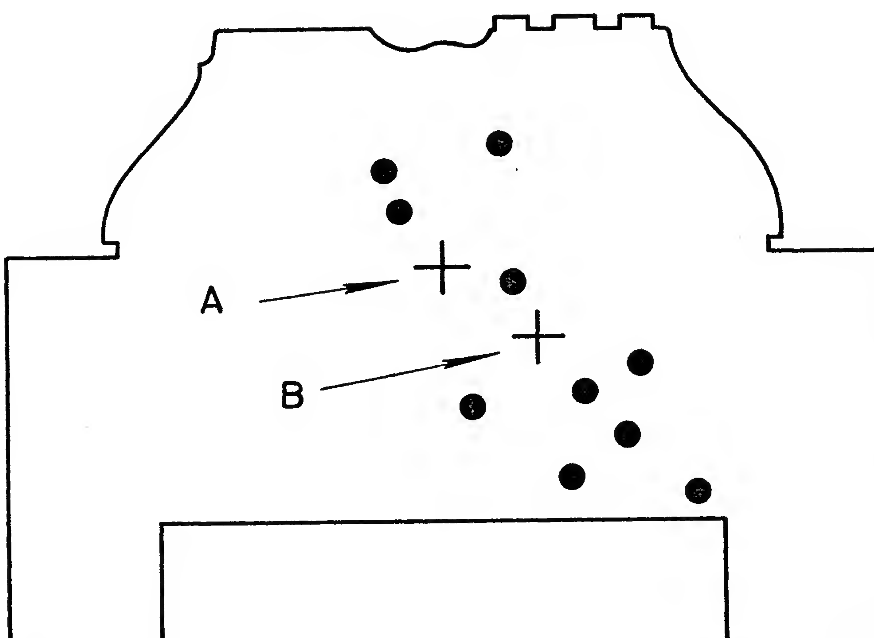


Fig. 7.6 Pattern of hits where A represents the aiming point and B the mean impact point.

cumulative density function $\Phi(t)$ of the standard normal distribution, which represents areas under the normal distribution curve from $-\infty$ to t and whose values are given in tables of the standard normal distribution (7.30). In consequence, the equation for the hit probability in elevation becomes, for purposes of calculation,

$$P_E = \Phi\left(\frac{\frac{h}{2} - y_m}{\sigma_y}\right) - \Phi\left(\frac{-\frac{h}{2} - y_m}{\sigma_y}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 7.3$$

There is a similar equation for the hit probability in azimuth. Values of the means and standard deviations of the distribution of impact errors are generally quoted in mils and to calculate hit probability from equation 7.3 it is necessary, therefore, to use not the height of the target but the angle θ_E which it subtends in mils at the given range R. The values of angles such as θ_E, which are small, are taken to be equal in mils to the ratio of the appropriate dimension of the target to its range multiplied by 1000. Hence,

$$\Theta_E = \frac{h}{R} \times 1000 \text{ mils} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 7.4$$

Thus, a target 2.3m high subtends 2.3 mils at 1000m, 1.15 mil at 2000m and so on. The mil is actually derived from the milliradian but whereas $2\pi \times 1000$, or 6283, millirandians are equal to one revolution the corresponding number of mils is rounded up to 6400. However, where the angles are small the definition of a mil implied in the above derivation of θ_E is sufficiently accurate.

The mean and the standard deviation of a distribution of impact points are made up of contributions from a number of different sources of errors. If the error sources are assumed to be mutually independent, the mean is, in fact, the algebraic sum of the means of the errors due to the different sources and the standard deviation is the square root of the sum of the squares of the standard deviations of these errors. In other words, taking dispersion in elevation as an example, the mean α_E and the standard deviation σ_E are, respectively,

$$\alpha_E = \alpha_{E_1} + \alpha_{E_2} + \alpha_{E_3} + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 7.5$$

$$\sigma^2_E = \sigma^2_{E_1} + \sigma^2_{E_2} + \sigma^2_{E_3} + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 7.6$$

The simplest approach to identifying the sources of errors is to divide the latter between ballistic errors and aiming errors. The ballistic errors can then be attributed to the gun and the ammunition and the aiming errors to the gunner and the fire control system. Such a division can be instructive but it is not sufficiently detailed to deal with the twenty or so sources of error. The more detailed approach which has been widely adopted to deal with them consists of classifying errors as fixed biases, variable biases and random errors and listing them, together with their various sources, under these three headings, the resulting lists being called error budgets.

Of the three classes of errors, fixed biases stem from the physical characteristics of the gun-fire control system, such as sight offset, and are constant at a given range. They can be allowed for, or minimised, by system design and consequently they are often left out of error budgets when comparisons are made of the performance of different gun and fire control systems.

Random errors are those which vary from round to round. They include ballistic errors due to the jump and throw off of the projectiles caused by the oscillations of the gun barrel, and to the variations in the mass of the propellant and in the muzzle velocity of the projectiles and their yaw. They also include gunner's aiming errors.

Variable biases are errors whose values are sensibly constant for any one group of shots but vary considerably from group to group, or from occasion to occasion. They include range-finding errors and errors due to trunnion tilt, environmental conditions and bending of the barrel due to differential heating or cooling. So far as single shots are concerned variable biases must be considered as random errors and their standard deviations are summed together with those of the random errors using equation 7.6 to give the standard deviations of the overall distribution of impact points in elevation and in azimuth.

Thus, for most practical purposes, all errors are taken to be random and error budgets amount to lists of their standard deviations. As long as range had to be estimated visually, the largest value item in the list of the standard deviations of vertical, or elevation, errors was due to range-finding errors and because of the nature of equation 7.6 these swamped all other errors. In that case the standard deviation of the total of errors in elevation with stationary tanks firing at static targets 1000m away has been of the order of 0.8 mil with high velocity ammunition such as APDS, and still only 1.6 mil for 2000m but as high as 4.4 mil even at 1000m with low velocity ammunition such as HESH.

With the adoption of laser rangefinders rangefinding errors have become very small and since then the largest errors have been due to the dispersion of the ammunition. As a result, the standard deviation of the total of errors with APDS has decreased to around 0.4 mil for the typical target range of 1000m.

The above illustrative values imply quasi-battle conditions, which are generally assumed in discussions of fire control systems and are meant to correspond to what happens on the battlefield but which do not consider the gunner to be under stress. In consequence, the standard deviation of the gun laying errors is taken to be only of the order of 0.1 to 0.2 mil, whereas under the stress of battle the gunner may aim far less accurately than these figures imply.

The above figures also imply a standard deviation of about 0.35 mil due to the ballistic dispersion of the ammunition, which has been typical of APDS under service conditions. Data corresponding to a standard deviation of only 0.18 mil have been given in the firing tables for APDS fired from the 105mm L7 gun but they are applicable not to service but to test range conditions, under which dispersion is generally considerably lower (7.31).

Under similar test range conditions the standard deviation of the ballistic dispersion of APFSDS projectiles has decreased to the even lower value of 0.15 or even 0.11 mil. These values are as low as any achieved with tank gun ammunition and are all the more remarkable in view of the relative complexity of APFSDS projectiles with their segmented sabots and the possibility of the sub-calibre projectiles being disturbed during their separation from the sabots.

7.6 Reaction Time and Automatic Tracking

In addition to contributing to the achievement of high hit probabilities, fire control systems should also contribute to reducing the time required to hit a target. This needs to be as short as possible for three reasons. First, targets commonly expose themselves for limited periods of time. Second, more than one target usually has to

be engaged. Third, the probability of a tank winning a duel with another tank, when the probabilities of a kill given a hit are the same for both, is in fact the probability that its time to hit is less than that of its opponent.

From the basis of the elementary concepts of probability theory it can be shown that the mean, or expected, time to hit t is given by the following equation,

$$t = t_I + t_F + (t_S + t_F)\left(\frac{1 - P_{H_I}}{P_{H_S}}\right) \qquad \text{7.7}$$

where P_{H_I} = probability of a hit with the first round
P_{H_S} = probability of hit with each subsequent round
t_I = time to fire the first round
t_S = time to fire each subsequent round
t_F = projectile flight time

It is evident from the above that the average time required to hit a target depends on the time to fire the first and subsequent rounds and on the time of flight of the projectiles as well as the probability of hitting it. Thus, the time to hit achieved with a given weapon system can be longer than with others even when its hit probability is high if, at the same time, it either takes relatively long to fire it or the projectile flight time is long. An example of the former was provided by the US M47 and M48 tanks with fire control systems incorporating stereoscopic rangefinders which were criticised for the time required with them to fire the first round, even though their hit probability was considerably higher than that of other contemporary tanks. An example of the latter has been provided by guided missile systems whose average time to hit is longer than that of tank guns, even though their hit probabilities are higher because of the relatively long missile flight times.

The time to fire the first round is typically made up of the times required to slew the gun on to the target, to coarse lay, to range, to fine lay and finally to fire. Given a fire control system with a laser rangefinder and an electronic computer, all this can be done in only 8 to 10 seconds, when the tank and its target are both stationary. Equally short times to fire can be achieved with simple, fixed battle sights but at some cost in hit probability, even with high velocity ammunition. With other fire control systems, which fall between these two extremes, the times have been significantly longer.

Even with the best fire control systems the first round hit probability is generally significantly less than one, which means than on average more than one round needs to be fired to hit a target. In consequence, the time to hit depends to a considerable extent on the hit probability and time to hit not only of the first round but also of the subsequent rounds, as indicated by equation 7.7. It can be reduced, therefore, by increasing the probability of hitting the target with the second or any subsequent rounds. In some cases this can be done by observing the distance by which the first round has missed the target and adjusting the lay of the gun according to it before firing the second round, or by automatic miss-distance sensing and gun lay adjustment, which is, of course, much more rapid.

Automatic miss-distance sensing and the consequent adjustment of the lay of the gun imply a closed-loop fire control system, instead of the usual open-loop systems. This further step in the development of fire control systems had already taken place with surface-to-air gun systems before it began to be explored in

relation to tanks in the mid-1970s as part of the US HIMAG test vehicle programme. In particular a closed-loop fire control system had been incorporated in the Phalanx surface-to-air gun system developed for the US Navy. But the latter was based on the tracking of projectiles by radar, which is not effective in a ground environment. In consequence, the closed-loop system of the HIMAG vehicle used a thermal imaging sensor in combination with a video tracker.

Analysis of miss-distance sensing has shown however that the effectiveness of closed-loop systems based on it depends on the nature of the gun-ammunition system and in particular on the relative magnitude of its variable biases and random errors. For instance, if there were no random errors, corrections based on target miss-distance could, in theory, increase the hit probability of a two-round ripple to one. On the other hand, when random errors predominate, as they do with any advanced fire control system, corrections based on target miss-distance can even degrade the hit probability of subsequent rounds. As a result, target miss-distance has been rejected as the basis of closed-loop fire control systems in favour of a comparison between the desired trajectory of the projectile and that determined by tracking it, and the consequent application of a statistically optimum correction to the next round (7.32). But, whatever improvement it might offer, the use of a closed-loop fire control system does not appear to justify its inevitable complexity and cost.

In addition to tracking projectiles, automatic video tracking can also be used to track targets. Its use for this purpose in tanks was first proposed in the mid-1960s in the United States by General Electric but its work on it did not advance beyond the laboratory stage. It was only in the late 1970s that Delco Electronics developed it to the stage where it could be incorporated in the fire control system of the HIMAG test vehicle. Soon afterwards Texas Instruments developed a second fire control system with what came to be called auto-tracking for the HSTV-L test vehicle.

The introduction of auto-tracking represents an advance from open-loop to closed-loop tracking of targets and offers the possibility of a significant increase in the probability of hitting moving targets by reducing aiming and tracking rate errors, particularly when the targets are manoeuvring (7.33). Alternatively, or in addition, auto-tracking can significantly reduce the time it takes to fire at moving targets, which is at least five to six seconds longer than the time to fire at stationary targets. In fact, it has been claimed that with the auto-tracker incorporated by Texas Instruments in the fire control system of the HSTV-L vehicle it is possible to engage moving targets five to ten times faster than with a human operator (7.34).

Auto-tracking has been based on a combination of a television camera imaging sensor with the gunner's sight and feeding its video output into a tracker, which locks on to the target and transmits data on the angular errors between the target and the line of sight to the fire control computer. The computer then generates rate command signals to close the line of sight on to the target and also generates displays in the gunner's video monitor. Since video trackers operate on the basis of contrasts between the target and the rest of the scene, there is a problem of discrimination between it and background clutter. This favours the use of thermal instead of visible images as tracker inputs, because they make the targets much more distinct.

The video trackers themselves have been of the gated type, which means that they have an electronically generated gate, or window, that encompasses the target and prevents scene information from outside the gated region interfering with the

tracking of the target. Tracking is based therefore on gated video signals that can be processed by different techniques, such as edge or centroid tracking (7.35). Edge tracking is the simplest of the techniques and involves the location of the edges of the target which are then tracked by the gate. Centroid tracking involves the determination of the centre of area of the target and using it as the tracking point. It is obviously more involved than edge tracking but less likely to suffer from loss of track lock-on, especially when targets disappear temporarily behind terrain features.

So far as the user is concerned, auto-tracking still requires the gunner to identify the target in the field of view using his monitor and to place the aiming mark on or near it. The tracker gate then expands to encompass the target and the tracker locks on to it and begins to track it automatically. Once auto-tracking has begun the gunner only needs to monitor the tracker lock-on display and to make any fine adjustment that might be required to the aim point before deciding to fire.

How effective automatic target tracking might be remains to be seen. It has been adopted for a number of anti-aircraft weapon systems but their targets move much faster and are much more difficult to track manually than ground targets. In fact, the speed of ground targets is such that the principal value of automatic target tracking for tanks might lie not in enhancing the accuracy of tracking from tanks that are stationary but when they are moving and engaging moving targets. However, the importance of this mode of engagement is questionable.

7.7 Threat Warning Systems

The ultimate result of automating the various fire control functions is a completely automatic fire control system. This means a system capable of acquiring and engaging targets without intervention on the part of the crew of the tank who would only monitor the performance of the system and retain, of course, overriding control.

The possibility of developing such a system was demonstrated in 1981 with an M60 tank modified by the US Army Tank-Automotive Command so that it could detect radiation impinging on it from, for instance, a laser target designator and then feed information about the direction from which the radiation was coming to the fire control computer to enable it to aim and to fire the tank's gun at the source of the radiation. The object of modifying an M60 in this way was not however to demonstrate specifically the possibility of developing a fully automatic fire control system. Instead, it was intended to demonstrate the feasibility of an automatic vehicle defence system which would combine threat warning devices with the fire control system and the main armament to provide tanks with an automatic counterfire capability.

The development of such defence systems may still lead to automatic fire control systems but in a different way from that followed in the development of fire control systems as such. In particular, the latter has generally taken the human operator as the initiator or starting point of any fire control sequence, with automation being applied to its subsequent stages. On the other hand, the development of vehicle defence systems has adopted sensors as the starting point of their operation and it began with the use of sensors only to provide warning signals for the crew of the vehicle, who then have to execute whatever follow-on action is appropriate.

Sensors have come to be used for this purpose because tank crews can not detect many of the threats which have come to face them by themselves. In particular, they can not sense the various forms of radiation outside the visible band of the

electromagnetic spectrum which are used to detect tanks or to direct weapons at them.

The earliest form of this radiation came from the searchlights of active infrared night vision systems and it was in response to their use that warning systems were developed for tanks. In consequence, the original warning systems consisted, in essence, of infrared detectors and generators of audible or visible warning signals. Their function was to alert crews when their tanks were being illuminated, of which they would not be aware unless their tanks were fitted with infrared or, more recently, image intensifier sights and they were scanning with them. Infrared warning systems of this kind were developed during the 1960s in the United States and in France and during the 1970s one was mounted in Britain on Chieftain tanks. However, they became superfluous to a large extent with the proliferation of infrared and image intensifier night sights.

During the 1970s attention turned to systems designed to provide warning of laser emissions. Thus, by 1973 TRT developed in France an improved version of their infrared detector which was also capable of sensing laser emissions. A little later Simrad developed in Norway a laser warning device especially for that purpose. A warning system capable of detecting infrared illumination and laser pulses was also developed in Israel by Amcoram for the Merkava Mark 2 and a more advanced warning system has been built from the start into the turret of Merkava Mark 3.

Concurrent development of threat warning systems for helicopters which incorporate radar as well as laser detectors has led to similar, more comprehensive systems being proposed for tanks. Examples of this include the TMV 518 system developed by 1981 in France by Thomson-CSF for helicopters and the Saviour threat warning system developed at about the same time in Britain by Racal Radar Defence Systems from the basis of their Prophet radar warning system and Simrad's laser detector. The detection of radar radiation is far less important for tanks than for helicopters but it has been included in warning systems proposed or developed for tanks because of the use of radar in some anti-tank missile guidance systems.

In addition to laser and radar radiation sensors, it has been proposed to fit tanks with other types of detectors. One of the earliest types to be considered were gun flash detectors but the benefits of installing them were judged to be insufficient to justify their adoption. The use of acoustic sensors has also been considered for detecting helicopters. Such sensors are potentially among the most valuable because of the difficulty of detecting helicopters flying close to the ground by other means and the threat which missile carrying helicopters pose to tanks. In fact, helicopters have been detected from tanks even when they were out of sight, behind terrain features, but only when the tanks were stationary and their engines were not running. Acoustic detection of helicopters under other circumstances has been prevented by the noise generated by tanks' own engines and running gear but the problems created by this may be overcome by adaptive filtering or counter-noise techniques.

The ultimate purpose of the various detectors would be not only to provide warning signals but also data for the fire control computers, so that they could initiate various reactions and it has been suggested that this might even include the engagement of incoming projectiles (7.36). More realistically, it has been proposed to fit tanks with surveillance and tracking radars by means of which they would automatically acquire and engage anti-tank guided missiles, using some kind of weapon to disable or to destroy them before they hit a tank.

Inevitably, the original laser and other warning systems only provide audible or visual warning signals for the crews of tanks who are then expected to take appropriate action, such as firing smoke grenades, chaff dispensers or infrared decoys, or performing evasive manoeuvres. How often such actions might be effective is debatable, because of the relatively slow speed of human reactions and the difficulty in many cases of discriminating between real and spurious threats. Some of these problems can be overcome by suitable procedures or tactics. But, in the end, to be effective to a high degree, warning devices need to be integrated with countermeasures and the latter activated automatically.

7.8 Burst, Ripple and Salvo Fire

Whatever fire control system is used, the probability of hitting a target can be increased by firing more than one shot at it. One way of doing this is by firing a burst of two or more rounds, which can be done with manually as well as automatically loaded guns, although, of course, the time between successive rounds can be considerably shorter with the latter.

Burst fire implies no adjustment to the lay of the gun between rounds so that, in theory, each shot has the same individual probability of a hit, i.e. $P_1 = P_2 = P_3 = P_n = P$. In that case the probability of scoring at least one hit P_H with n shots is given by

$$P_H = 1 - (1 - P)^n \qquad \text{7.8}$$

The improvement in hit probability which can be obtained by firing bursts of two or three rounds instead of single shots is illustrated in Fig. 7.7 and is evidently greater than anything that might result from further developments in fire control systems. However, the probability of scoring a hit does not increase as rapidly with the number of rounds as might be expected, particularly when the single shot hit

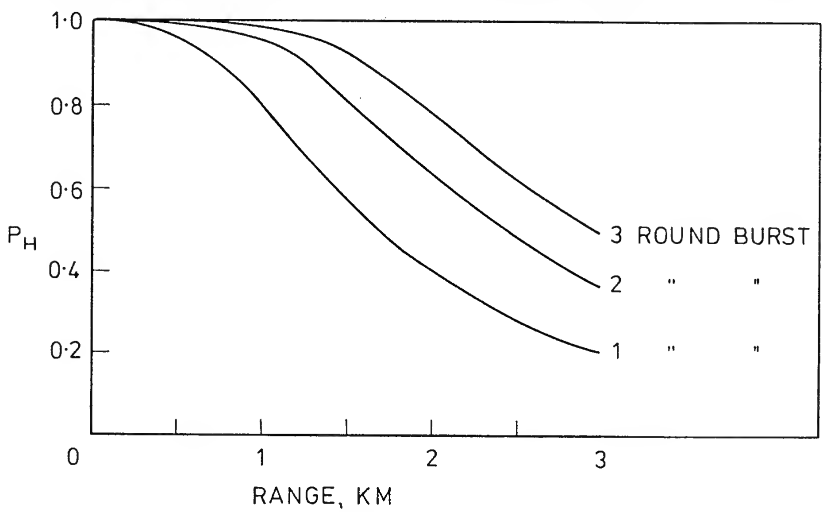


Fig. 7.7 Hit probability versus range for a single shot and bursts of two and three rounds.

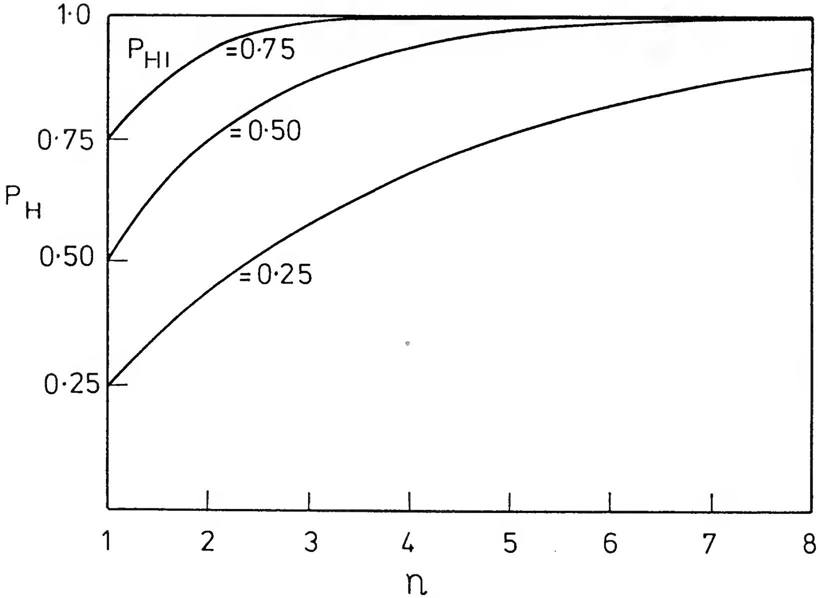


Fig. 7.8 Probability of scoring at least one hit plotted against the number of rounds fired for three different single shot hit probabilities.

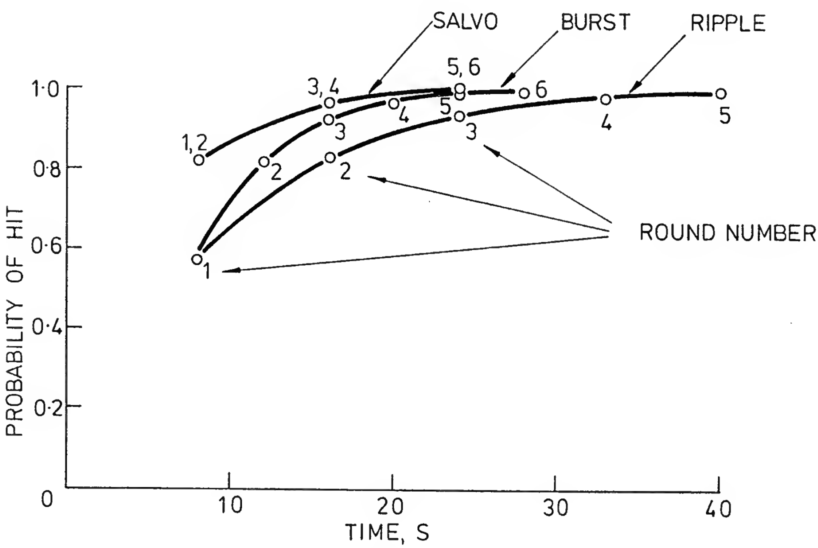


Fig. 7.9 Hit probability versus time for burst, ripple and salvo fire.

probability is low, as it is at longer ranges. This is illustrated by the curves of at least one hit versus the number of rounds fired, which are shown in Fig. 7.8.

The alternative to burst fire is what with automatically loaded guns has been called ripple fire. This implies that the lay of the gun is adjusted between successive shots so that their individual hit probabilities increase from one shot to the next, i.e. $P_1 < P_2 < P_3$, etc., although the time interval between shots also increases. In that case, the probability of scoring at least one hit P_H with n shots is given by

$$P_H = 1 - (1 - P_1)(1 - P_2) \dots (1 - P_n) \qquad \dots\dots\dots\dots\dots\dots \; 7.9$$

The probability of hitting a target can also be increased by firing salvoes of two or more rounds. This implies, of course, the mounting of a corresponding number of guns and penalties in terms of additional components and weight. Nevertheless, several vehicles have been built with multi-gun installations capable of firing salvoes. The extreme example of them was the M50 Ontos anti-tank vehicle developed in the United States during the 1950s, which had six 106mm recoilless guns and was, therefore, capable of firing salvoes of up to six rounds. The installation of as many as six guns on the Ontos was made possible by them being recoilless. But the development in Germany during the 1970s of the VT-1-1 and VT-1-2 experimental turretless vehicles with two 105 and 120mm tank guns, respectively, showed that twin tank gun installations were possible.

Assuming that there is no adjustment to the lay of the guns and that each shot has the same individual hit probability, the probability of scoring at least one hit by salvo fire can be treated in the same way as in the case of burst fire but with the hit probability of a salvo replacing the hit probability of a single shot.

The relative effectiveness of the three different modes of fire is illustrated in Fig. 7.9, which shows curves of hit probability versus time. The curves relate to the engagement at about 1500m of a standard, 2.3m x 2.3m target with 105mm guns firing APDS ammunition and involve the assumption that the time interval between shots in burst fire is half the time between shots in ripple fire and between the salvoes of two rounds.

The curves indicate that salvo fire is an effective way of increasing the probability of hitting targets at the outset of an engagement. But beyond the second salvo it becomes less effective than burst fire in relation to the number of rounds fired. The most effective in the latter respect is ripple fire, as one might have expected, but it takes longest to hit the target under the assumed conditions.

7.9 References

7.1 *Instruction sur l'Armement et le Tir dans les Unites de Chars Legers*, Charles-Lavauzelle, Paris, 1937, p.94.

7.2 P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978, p.126.

7.3 W Wrigley and J Hovorka, *Fire Control Principles*. McGraw-Hill, New York, 1959.

7.4 K I T Richardson, *The Gyroscope Applied*, Hutchinson, London, 1954.

7.5 *Oerlikon Pocket Book*, Oerlikon-Bührle, Zurich, 1981, pp.319-330.

7.6 R M Ogorkiewicz, 'An Advanced Tank Fire Control System', *Armor*, Vol.80, No.1, January-February 1971, pp.28-31.

7.7 S Feinstein, 'The Evolution of the Tank Fire Control System', *Armor*, Vol.82, No.1, January-February 1973, pp.21-24.

7.8 W L Warnick and R A Baker, *The Tank Commander's Guide*, Stackpole, Harrisburg, 1963. pp.401-406.
7.9 W J Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, pp.124 and 288-289.
7.10 R M Ogorkiewicz, *S-Tank*, AFV/Weapon Profile No.28, Profile Publications, Windsor, 1971.
7.11 T Smith, 'Periscopes', in R Glazebrook, ed., *A Dictionary of Applied Physics*, Vol.IV, Macmillan, London, 1923.
7.12 H H Emsley and W Swaine, 'Rangefinders', in A Gleichen, *The Theory of Modern Optical Instruments*, Stationery Office, London, 1918.
7.13 F J Cheshire, 'Range-finders, Short-base', in R Glazebrook, ed., *A Dictionary of Applied Physics*, Vol.IV, Macmillan, London, 1923.
7.14 L A Hammack, 'Range Finder Training', *Armor*, Vol.63, No.5, September-October 1954, pp.26-27.
7.15 H L Rogers, 'Why Not Use the Rangefinder?', *Armor*, Vol.67, No.3, May-June 1958, pp.47-49.
7.16 G T Neu, 'Home on the Range', *Armor*, Vol.72, No.1, January-February, 1963, pp.39-41.
7.17 R Knecht, ed., *Leopard Combat Tank*, Lehmanns, Munich, 1972, p.95.
7.18 A Gleichen, *The Theory of Modern Optical Instruments*, Stationery Office, London, 1918.
7.19 W J Spielberger, op.cit., pp.225-226
7.20 J M Warford, 'The T95: A Gamble in High-risk Technology', *Armor*, Vol.92, No.4, September-October 1983, pp.39-41.
7.21 B A Lengyel, *Lasers*, Wiley, New York, 1971.
7.22 R M Ogorkiewicz, 'Developments in Tank Design', *The Engineer*, Vol.216, No.5622, 25 October 1963, p.668.
7.23 G R Elion and H A Elion, *Electro-Optics Handbook*, Marcel Dekker, New York, 1979.
7.24 R R Robinson, *Developments in Sighting for Armoured Fighting Vehicles*, High Technology in Defence Symposium, Brighton, 1981.
7.25 A M Johnson, *Hand-held Laser Rangefinders – System Constraints*, Electro-Optics/Laser 81 Conference, Anaheim, November 1981.
7.26 R T Bulova, *Advances in 2nd Generation Solid State Laser Rangefinders*, Electro-Optics/Laser 81 Conference, Anaheim, November 1981.
7.27 D A Malcolm, *Laser under Armour*, Ferranti, Edinburgh, c.1981.
7.28 D E Hendrix, R L Duvall and R V Salotti, *A Carbon Dioxide Laser Rangefinder for the M1 Tank*, Electro-Optics/Laser 81 Conference, Anaheim, November 1981.
7.29 *The Laser Rangefinder*, Marconi Avionics, Borehamwood, 1979.
7.30 *Handbook on Weaponry*, Rheinmetall, Düsseldorf, 1982, pp.206-207.
7.31 Y Brunin, 'A Chars Modernes – Conduites de Tirs Modernes (II),' *Bulletin de Cavalerie*, No.234, Stockem-Heinsch, November 1969.
7.32 *An Overview of Fire Control at Delco Electronics*, Delco Electronics, Santa Barbara, c.1979.
7.33 M A Leu and R P Baker, *Video Auto-Tracking for Combat Vehicles*, Symposium for Army Aircraft and Combat Vehicle Fire Control, Dover, 1977.
7.34 *High Survivability Test Vehicle*, Texas Instruments, Dallas, c.1980.
7.35 W L Wolfe and G J Zissis, *The Infrared Handbook*, Office of Naval Research, Department of the Navy, Washington, 1978.
7.36 B L Lewis, 'Tank Fire Control', *Countermeasures*, Vol.2, October 1976, pp.42-45.

Chapter 8

Gun Control Systems

8.1 Development of Gun Control Equipment

The movement or positioning of the armament of a tank in elevation and in azimuth requires an appropriate gun control system. The operation of any such system is governed, in general, by the requirements of the tank's fire control system. But although it is closely connected and sometimes confused with the latter, it has its own distinct function of controlling the main armament of a tank in space.

In the original British tanks of the First World War and in other early tanks such as the Renault FT, the guns were mounted so that they were free to pivot about their trunnions and gunners controlled them in elevation by pressing on a shoulder piece attached to the gun cradle. The free elevation type of mounting and shoulder control had the advantage of being extremely simple and they continued to be used in British, French and other light tanks up to the early stage of the Second World War. In Britain they were used even longer in heavier tanks. This was largely due to the preoccupation of the Royal Tank Corps during the 1930s with firing on the move, for which free elevation and shoulder control were considered more suitable than the hand-crank operated elevating gears which were fitted in the Vickers Mediums of the 1920s (8.1). Thus, shoulder control was used in British cruiser and infantry tanks from the A.9 designed in 1934 to the Cromwell and Churchill tanks of 1943 and was only abandoned in the latter when their 57mm 6-pounders were superseded by 75mm guns.

Elsewhere the heavier types of tanks were fitted with manually operated elevating gears from the late 1920s onwards and even in Britain Vickers-Armstrongs used them in their widely copied Six-Ton Tank, which was designed in 1928 but not to British Army requirements. An exception to the general trend was provided by the US Christie-type T3 medium tank of 1931, in which the elevation was still shoulder controlled. However, by 1939 not only the US M2A1 medium tank but also the M2A4 light tank were fitted with geared elevation (8.2).

Manually operated gears are a more precise if somewhat slower means of controlling the elevation of guns than shoulder pieces and they are still relatively simple, light and inexpensive. As a result, they have continued to be used in light tanks and other light armoured vehicles. An example of this is the British Scorpion light tank produced during the 1970s. Until 1945 manually operated gears were also the only means of elevating guns in most medium and heavy tanks, including the German Tiger II heavy tank as well as the Soviet T-34-85 medium and the IS-3 heavy tanks.

Control of guns in azimuth was exercised in some of the early light tanks, such as the Renault FT, by the gunner simply pulling or pushing against the sides of the turret, which was free to rotate when not locked in position (8.3). This primitive method of traversing weapons is still used with machine guns mounted on rotating commander's cupolas of light armoured vehicles or on simple ring mountings but it could not be used with turrets heavier than those of the Renault FT. Thus the turrets of the Vickers Mediums, which were first built in 1923, were fitted with traversing gears and by 1930 even the Light Tank Mark II was fitted with them, even though the weight of its turret was much the same as that of the Renault FT.

The traversing gears consisted, in essence, of a hand crank driven pinion which was attached to the turret and engaged with the internal teeth of a ring gear fixed to the hull. The drive from the crank to the pinion was transmitted by a train of reduction gears, which were refined over the years and eventually transformed into two-speed gearboxes. Nevertheless, manual operation of the traversing gears severely restricted the speed with which turrets could be traversed, particularly as they grew in size and weight. In consequence, the heavier types of tanks began to be fitted with powered traverse.

An early example of this were the German experimental *Grosstraktoren* built in 1929, which were fitted with electric motors to traverse their turrets in addition to a manual traverse drive (8.4). Electric turret traverse was subsequently put into service in the Pz.Kpfw.IV, which began to be built in 1937, and by then an electric traverse drive had also been adopted for the APX turrets of the French Char B and the S-35 tanks (8.5). By 1940 electric traverse drives were also adopted for the Soviet KV and T-34 tanks.

The electric traverse drives fitted in the Char B, S-35, T-34 and KV tanks were of a simple nature and although they could slew turrets more rapidly than hand traverse they did not provide sufficiently precise control for accurately laying guns on target, which still had to be done manually. However, this was no longer the case with the electric traverse drive fitted by Vickers-Armstrongs in 1940 in the Valentine infantry tank, which could be used not only for rapidly slewing the turret but also for fine laying.

Electric power traverse was also used in the Churchill infantry tanks but until the introduction of the Comet in 1944 other British tanks had a hydraulic traverse drive, which was first fitted in 1936 in the A.9 cruiser tank. The adoption of the hydraulic drive was influenced by the contemporary development of the Frazer-Nash hydraulic system for the turrets of bomber aircraft and it provided a power drive with a speed range wide enough to cover the needs of turret motion from fast slewing to slow, fine traverse.

By 1940 hydraulic turret traverse had also been adopted in Italy for the M13/40 medium tank and by 1941 in the United States for the M3 medium tank. It was then also fitted in the US M4 medium as well as M3A1 and later light tanks and in the German Tiger and Panther tanks. Since the Second World War hydraulic traverse systems have continued to be used in US and German tanks. They have also been fitted in French and Swiss tanks and in the first two versions of the Israeli Merkava. On the other hand, British and Soviet tanks and the Japanese Type 74 have been fitted with electric traverse drives.

The use of electrically or hydraulically powered systems for traversing turrets was followed by the adoption of powered controls for the elevation of tank guns. The latter were originally introduced to make it possible to stabilise tank guns in elevation, so that they could be fired on the move with a greater probability of

hitting targets. Stabilisation of guns had been used before in warships and this may have inspired its original application in tanks. In any case, a crude stabilisation system was tried in 1938 in the US M2A2E3 light tank (8.6). At about the same time other attempts to stabilise tank guns appear to have been made in the Soviet Union (8.7). However, it was only in 1941 that stabilisation of guns in elevation was first adopted in the United States for both the turret-mounted 37mm and the hull-mounted 75mm guns of the M3 medium tank.

Stabilisation was subsequently applied to the guns of the US M4 medium tanks, of light tanks from the M3A1 onwards and even of armoured cars, such as the T17E1 or Staghound. However, the stabilisation systems fitted in all these US vehicles did not prove of great practical value during the Second World War and for some time afterwards US tanks were produced without them. The T37 light and T42 medium tanks designed after the war actually had their turrets stabilised in azimuth as well as having their guns stabilised in elevation but they were not put into production. On the other hand, the M41 light, M47 and M48 medium and M103 heavy tanks which were produced during the 1950s had no stabilisation systems. Neither did the M60 and M60A1 tanks which were produced during the 1960s and it was only during the 1970s that the M60A2 and then the M60A3 were produced with stabilised controls.

Similarly, German Leopard 1 and French AMX-30 were produced during the 1960 without stabilisation and although Leopard 1 began to be retrofitted with it in 1972 it was still not adopted for the AMX-30 B2, which was first issued to French tank units in 1982.

In contrast, British Centurion tanks incorporated stabilised controls of both the gun in elevation and of the turret in azimuth from 1945 onwards and the Conqueror, Chieftain and Challenger tanks which followed have had similar controls. Stabilised controls were also fitted in Soviet tanks, starting with the T-54 although not in its original version introduced around 1949. Moreover, when they appeared in the early 1950s in the T-54A they were still confined to the elevation of the gun. However, soon afterwards the turret of the T-54B was also stabilised and since then all Soviet battle tanks have had turrets stabilised in azimuth as well as having guns stabilised in elevation.

In the 1960s attempts began to be made in Germany to apply stabilisation not only in elevation and in azimuth but also in roll. This involved the development of a three-part turret in which the top part was mounted on trunnions so that it could rotate in the elevation plane, like the upper part of a trunnion-mounted or oscillating turret. But, in contrast to the latter, the trunnions were not mounted directly in the bottom part of the turret but in the circular bearing which allowed them to rotate in their roll plane relative to the bottom part; the latter was mounted on the hull on the usual type of circular turret bearing and rotated in azimuth.

Since the crew seats as well as the gun and the sights were all fixed to the top part of the turret, the crew were stabilised about three axes, and not only in azimuth as they are in the other cases where the turrets are stabilised. This meant that the turret crew were decoupled from the pitching and rolling of the chassis and to this extent a tank fitted with such a turret could move faster over rough ground. However, a three-part turret stabilised about the three axes was inevitably complicated, its configuration was ballistically poor and its operation consumed a considerable amount of power. It is not surprising therefore that the development of tank-size turrets of this kind did not advance beyond one armed with a 105mm gun which was mounted on a modified Leopard 1 chassis in 1966 (8.8).

Nevertheless, the concept of a turret with stabilisation about the three axes was

considered worth exploring further for lighter vehicles. Thus, the Rheinstahl company built in Germany a smaller, two-man turret of this kind which was armed with a 20mm gun. The turret, designated LWT-3, was mounted on a Marder infantry armoured vehicle and tests of it began in 1972. But, in spite of the advantages claimed for it, no turret of its kind has been adopted (8.9).

So far as the crew are concerned, the greatest potential advantage lay in the extension of the stablisation of the turret to its motion in elevation. But this could have been achieved without going in complexity beyond the trunnion-mounted or oscillating turrets, several of which had already been developed. Curiously, none of them appears to have been stabilised until the construction of the improved versions of the Steyr SK 105 Kürassier in the mid-1980s. Otherwise all that the three-part turret offered was an extension of the stabilisation of the gun to the roll axis and the case for this disappeared with the contemporary development of computer-based fire control systems and of independently stabilised gunner's sights, which between them could take care of any roll of the gun trunnions.

The first tank to have an independently stabilised gunner's sight was the US-German MBT-70, which appeared in prototype form in 1967. Until then all gunner's sights were either fixed to the gun mounting or mechanically linked to them. But the example of the MBT-70 has been followed by several tanks, starting with the Leopard 2. The US M1 is another early example of a tank with an independently stabilised gunner's sight but stabilised only in elevation, whereas Leopard 2, like the MBT-70, and several more recently built tanks have sights stabilised in azimuth as well as elevation.

The development of gunner's sights stabilised independently of the guns has been accompanied by the electronic slaving of the guns to the sights, in place of the mechanical slaving of the sights to the guns. This has resulted in the latest tanks having director-type fire control systems and a higher probability of hitting targets on the move than before.

8.2 Electric and Hydraulic Power Drives

In their simplest form electric traverse drives consist of an engine-driven generator, a rotary base junction to transmit the power from the hull to the turret, a DC motor driving a reduction gearbox and a unit for controlling the speed of the motor, and hence the rate of traverse, in response to changes in the position of the gunner's control handle. Open-loop systems of this kind were still being developed for light armoured vehicles during the 1970s but other systems produced since the Second World War have been of a more sophisticated, closed-loop type with an output velocity feedback obtained by adding a tacho-generator to the motor. Thus tacho-generator feedback signals, which are proportional to the angular velocity of the turret, have been compared with the speed demand signals from the gunner's controller and any difference between the two, or system error, used to automatically adjust the speed of the turret to nullify the error. This has absolved the gunner of the need to adjust the position of his controller on account of random changes in the operating conditions of the traverse system, or because of disturbances to it, and has made the control of traverse more accurate and more consistent.

Similar electric servo controls have been applied also to the elevation of tank guns. The more powerful electric systems developed since the Second World War have also incorporated amplifiers to deliver power to the traverse and elevation servo motors. In the British tanks, from the Centurion to the Challenger, the power amplifiers have been metadynes. These are generators, driven by electric motors,

whose field current is controlled electronically and which require relatively little of it to control a much larger output current. Their response is also very rapid (8.10). A somewhat different type of rotary power amplifier, the amplidyne, has been used in the T-54 and other Soviet tanks and was also tried in a number of US tanks during the 1950s (8.11).

During the 1980s rotary power amplifiers began to be superseded by solid-state semi-conductor power amplifiers, which are more efficient, silent and require no maintenance. One such amplifier was actually built in the United States by General Electric and was tested in a M60 tank as early as 1967. But the first to be adopted was an amplifier developed in Britain by Marconi Radar Systems, which was installed in a Vickers Valiant prototype built in 1980 and then in the Osorio built by the Engesa company (8.12).

The alternative, hydraulic traverse drives consist, in essence, of a positive displacement hydraulic pump delivering fluid under pressure to a positive displacement hydraulic motor connected to the traverse gears. There are, however, considerable differences between the various hydraulic drive systems in the way the flow of fluid from the pump to the motor is controlled and in other respects.

The early type of hydraulic drive used in British tanks such as the Cromwell employed a variable displacement, axial-piston, tilting swash-plate pump which was self-regulating and delivered fluid at virtually constant pressure to a hydraulic valve unit. A throttling valve in the unit controlled the rate of fluid flow to a vane-type fixed displacement motor, and hence the speed of rotation of the turret, according to the angular position of the gunner's control handle. The latter was also linked to another valve controlling the direction of the fluid flow to the motor and therefore the sense of rotation of the turret (8.13).

A very different control method was used in the hydraulic drive produced by the Oilgear Company for the US M4 medium and other tanks. In this case the pump was of the variable-displacement, radial-piston type and the rate as well as the direction of the fluid flow from it to a fixed displacement, axial-piston motor were controlled by varying the stroke of the pistons by changing the eccentricity of the track against which they bear, the track being linked to the gunner's control handle. A similar method of control was used in the CH 1 hydraulic drive designed in France in 1948 by SAMM for the Panhard EBR eight-wheeled armoured car but in this case both the variable displacement pump and the fixed displacement motor were of the radial-piston type (8.14).

However, the CH 6 hydraulic system produced by SAMM from 1954 onwards for the AMX-13 light tank reverted, in principle, to the arrangement adopted earlier for the hydraulic drives of British tanks. The same arrangement was subsequently embodied in the CH 27 system developed for the AMX-30 tanks as well as the CH 25 system produced for the Swiss Pz.61. Thus the SAMM hydraulic drives came to consist of a self-regulating variable-displacement pump, of the axial-piston, bent-axis type, which delivered fluid through a throttling valve controlled directly by the gunner's handle to a fixed-displacement, radial-piston motor.

Systems of this kind in which the flow of fluid to the motor is controlled by a throttling valve are basically less efficient in terms of power consumption than systems in which the flow is controlled by varying the displacement of the motor. But valves lend themselves to accurate metering of fluid at low rates of flow and provide therefore the control necessary for precise, slow-speed traverse of the turret, as well as allowing rapid slewing.

In consequence, systems with throttle valve control of the fluid flow to the motor came to be preferred not only in France but also in the United States. The

preference expressed itself in the decision taken in 1955, after exhaustive trials, to abandon the earlier Oilgear system in favour of a Cadillac Gage system, which was adopted for the M48A2 tanks. Similar systems were subsequently adopted for the M60, M1 and the Korean Type 88 tanks and they have also been produced in Germany by Feinmechanische Werke Mainz for the Leopard 1 and 2 and in Israel for Merkava Mark 1 and 2.

Although it employs basically the same type of flow control as the original British and the French SAMM hydraulic systems, the Cadillac Gage system differs from them in having an accumulator as a source of constant pressure. The accumulator is charged with fluid from a reservoir by a pump that can be of a simple, gear type and fluid flows from it to a fixed displacement motor through a valve assembly connected to the gunner's control handle which governs the rate and the direction of flow, and hence of the turret traverse, as in the other systems.

Apart from the differences in the method of controlling the flow of fluid and in the types of pumps and motors, hydraulic drives also differ in the way in which the hydraulic pumps are powered. In most cases the pumps have been driven by an electric motor supplied with power by the vehicle's electrical system and the majority of the drive systems have been therefore electro-hydraulic. However, in the early British hydraulic systems of the kind fitted in the Cromwell the pump was driven directly by the engine. The use of an engine-driven pump then lapsed but was revived in the 1960s in the MBT-70 and has been continued since in the US M1 and the Korean Type 88 tanks. In principle hydraulic systems with engine-driven pumps are more efficient and lighter than electro-hydraulic systems but they require the use of a hydraulic rotary junction, or 'hydraulic slip ring', to allow fluid to flow from the pump, which is in the hull, to the motor in the turret.

Most of the features of hydraulic traverse drives have been duplicated in hydraulic elevation drives, which have come into use since the Second World War. The principle difference has been the use of a hydraulic piston actuator, or ram, instead of a motor and reduction gears, although the latter have been used to control gun elevation in the SAMM CH 25 system of Pz.61. In general, hydraulic elevation drives have been a logical complement to hydraulic traverse drives but in Soviet tanks, such as the T-54, T-55, and T-62, they have been used in conjunction with electric traverse drives.

The use of electric and hydraulic drives inevitably raises questions about their relative merits. A clear advantage of the hydraulic systems is that they can hold large out-of-balance loads, which may exist about the traverse or elevation axes. In addition to their normal functions, hydraulic motors and actuating cylinders can also act as brakes and they are smaller and lighter than electric motors with their reduction gears. But the total volume of hydraulic systems is much the same as that of electric systems and there are several disadvantages to them in other respects.

The most serious disadvantage of hydraulic systems is the risk of fire or explosion, which arises from the escape of the hydraulic fluid from a system damaged in battle and the possibility of its ignition, particularly by shaped charge jets. Even when there is no fire there is still the risk of the crew being injured by the hot fluid escaping under high pressure from a ruptured system and there is the ever present possibility of fluid leaks, which at best are a nuisance. Another major disadvantage of hydraulic systems is the possibility of them failing due to the contamination of the fluid by dirt or wear particles, unless considerable care is taken not only during their assembly but also in the maintenance of the systems, which need to incorporate fine filters. A further disadvantage of hydraulic systems is that the viscosity of

the fluid used in them inevitably varies with temperature, which may result in their performance being degraded when starting from cold until the fluid has warmed up, and this may take a significant period of time.

None of these problems exist with electric systems, which are much safer for tank crews in the event of battle damage. On the other hand, the efficiency of electric systems with rotary power amplifiers is only in the range of 30 to 55 per cent, whereas that of hydraulic systems lies between 40 and 65 per cent. However, the efficiency of electric systems with solid state power amplifiers is even higher, being typically of the order of 80 per cent. The high efficiency means that there is less heat to be dissipated with solid state electric systems because of power losses and, unlike the other systems, they are quiet, require little if any routine maintenance and are instantly available.

The performance of both electric and hydraulic systems has improved considerably over the years. For example, the early type of electric traverse drive fitted in the French S-35 tanks provided a maximum turret speed of 10 degrees per second. This was no faster than the speed with which a relatively light turret could be traversed with manually operated gears, although it could be achieved, of course, without physical effort and ultimately fatigue on the part of the gunner. Moreover, the minimum speed of the early systems, and even of some relatively recent but simple systems, has not been low enough for fine laying. So, while they could be used for slewing turrets, the guns still had to be laid on target manually.

Maximum turret speeds obtainable with hydraulic drives produced during the Second World War, such as the Oilgear drive fitted in the US M4 medium tanks, increased to 24 deg/sec and speeds of this order were typical until recently of both electrically and hydraulically driven turrets. Although speeds have increased further, traverse rates of 24 deg/sec were already beyond the capabilities of manually driven systems, even if the mass and the moment of inertia of the turrets had not increased as they did. Thus, a lightly armoured two-man turret having a mass of 2000kg and a moment of inertia about the traverse axis of about 1000kg m^2 could still be traversed adequately by manually driven gears. But a three-man turret with a 75mm gun of a typical Second World War tank such as the US M4 medium already has a mass of 5500kg and a moment of inertia of 5000kg m^2 and tanks produced since then have had much heavier turrets. For instance, Centurion III had a turret with a mass of 13 700kg and a moment of inertia of 24 000kg m^2 while more recent, heavily armoured tanks armed with 120mm guns have turrets with a mass of 16 000kg and a moment of inertia of 35 000 to 40 000kg m^2, which make power drives imperative.

While maximum traverse speeds changed little between the mid-1940s and the late 1960s, the minimum speeds of traverse decreased very considerably, extending the speed range of turret drives to speeds low enough for fine laying. Thus, turret drives produced during the late 1940s provided minimum speeds of 1 mil/sec but this was improved upon during the 1960s, when a number of systems were introduced with a minimum speed of 0.5 mil/sec, and during the 1980s traverse drives were introduced with a minimum speed of 0.2 or even 0.1 mil/sec.

The need for very low minimum speeds was emphasised by the installation on turrets of guided missile systems with semi-automatic, command-to-line-of-sight guidance which requires very accurate tracking. In consequence, the traverse drive developed by General Electric for the turret of the US M2 Infantry Fighting Vehicle, which mounts TOW missile launchers, provides a minimum speed of only 0.05 mil/sec. The drive is electric and it proved better able to provide such low

speeds than hydraulic drives, which are restricted to somewhat higher rates of traverse by the torque ripple of their hydraulic motors. The drive of the M2 IFV can also provide a maximum traverse rate of 60 deg/sec, which means that it has a speed range of as much as 21 000 to 1.

Similarly high traverse speeds have been provided in some tanks in response to the increase in their speed and manoeuvrability. For instance, the US-German MBT-70 of the 1960s already had a maximum traverse rate of 60 deg/sec and the US HIMAG test vehicle of the late 1970s and 1980s even had a maximum rate of 80 deg/sec. Rates as high as this have not been used in any tank produced in quantity. But there has been a trend towards the higher rates of 40 to 45 deg/sec and traverse drives of tanks such as the Leopard 2 achieve them already.

The elevation rates of tank guns have improved to a similar extent. For instance, the maximum elevation rate has increased from 4 deg/sec of the US M41 and M60A1, through 6 deg/sec of the AMX-30 and 8 deg/sec of the MBT-70, to 10 deg/sec of the Leopard 2. Minimum elevation rates decreased at the same time from 1 mil/sec of the M41 through 0.5 mil/sec of the Chieftain to 0.2 mil/sec of the Challenger.

8.3 Stabilisation of Guns and Turrets

Motion of vehicles causes unwanted movements of the guns mounted in them which must be minimised if the guns are to be fired on the move with any chance of hitting their targets. Gunners have been expected to compensate for vehicle motion, particularly in the elevation plane, by rotating guns in the opposite sense to that of the angular motion of the vehicles but this generally consists of oscillations at frequencies which go beyond what human reactions can cope with. In fact, the frequency of vehicle motions ranges from 0 to 3 or 4Hz, whereas the response bandwith of human operators is not much more than about 0.5Hz.

However, the effects of vehicle motion can be minimised by gun stabilisation systems which are designed to maintain the spacial orientation of guns in spite of the pitch, yaw and roll of moving vehicles. Systems designed to do this are basically closed-loop servo systems which control the orientation of guns relative to the inertial space by employing gyroscopes to sense the motion of the guns relative to it and using position or velocity feedback signals provided by the gyroscopes to drive the guns in a way which minimises the difference between the desired and the actual orientation or rotation of them.

The simplest stabilisation systems have been confined to the elevation of guns and consist, in essence, of a single closed-loop servo system with a rate gyroscope mounted on the gun to sense its angular velocity. Any difference between this velocity and that commanded by the gunner causes the elevation servo-motor, or actuator, to rotate the gun so that the difference, or 'error', is minimised and if the gunner holds his controls steady the system maintains the gun at a fixed elevation relative to space.

Systems of this kind were used in most of the US tanks in which stabilisation was originally introduced during the Second World War and also when it was first applied in Soviet T-54 tanks. The argument for stabilising guns only about the elevation axis has been that disturbances about the other axes are much smaller and, therefore, less important. However, disturbances about the traverse axis of the turret are not insignificant and except for the original stabilisation systems all the others have stabilised the turrets in azimuth in addition to stabilising the guns in elevation.

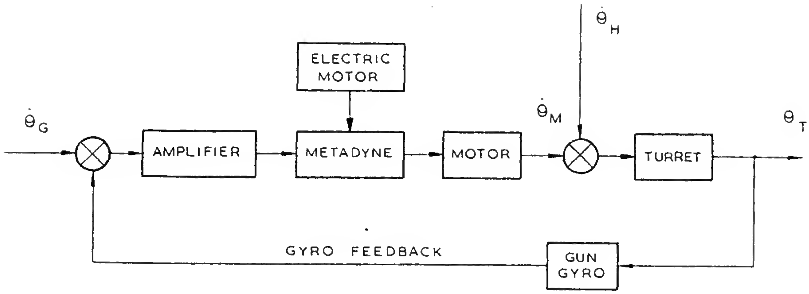


Fig. 8.1 Simplified block diagram of an all-electric traverse drive with gyro velocity feedback:
$\dot{\theta}_G$ = *gunner's velocity command*
$\dot{\theta}_H$ = *hull azimuth rate*
$\dot{\theta}_T$ = *turret azimuth rate*
$\dot{\theta}_M$ = *traverse motor velocity*

A two-axis stabilisation system developed by Westinghouse was already fitted during the Second World War in some US M4 medium tanks but the effectiveness of this type of system was not established until one was produced after the war for the British Centurion tanks. The system used in them was originally developed by the Metropolitan-Vickers company and was developed further by its successor, Marconi Radar Systems, who produced similar systems for the Indian Vijayanta tanks designed by Vickers and for Vickers' Mark 3 tanks. It also served as a model for the system produced for the Chieftain by GEC Electronics and the very similar system fitted in the Challenger.

All these British produced systems have used electric drives and two rate gyroscopes mounted on the gun cradle to sense the angular motion of the gun in elevation and of the turret in azimuth. A block diagram of one of the two stabilised drives of these systems is shown in Fig. 8.1, which illustrates their unique feature, namely the use of metadynes as power amplifiers. The diagram happens to be of the traverse drive but is equally illustrative, in principle, of the elevation drive.

Some stabilisation systems used with electro-hydraulic power drives are basically similar but in place of the electric servo-motors use hydraulic motors for traversing turrets and double-acting hydraulic rams for elevating guns. Systems of this kind are exemplified by those developed by Honeywell for the Swiss Pz.68 and US M60A3 tanks.

Stabilisation systems with one rate gyroscope in the elevation drive and a second in the traverse drive have proved reasonably effective in attenuating disturbances of the spacial orientation of guns. But their performance is constrained by what can be achieved with simple servo-loops in terms of loop gains, which determine the degree of disturbance attenuation and the range of frequencies, or bandwidth, over which high loop gains can be used without the system becoming unstable. In consequence more sophisticated, 'second generation' stabilisation systems incorporate additional rate gyroscopes which respond directly to the angular velocity of vehicles, instead of responding to its effect on the guns, and provide the basis for additional, feed-forward, open-loop control. The latter commands gun motion

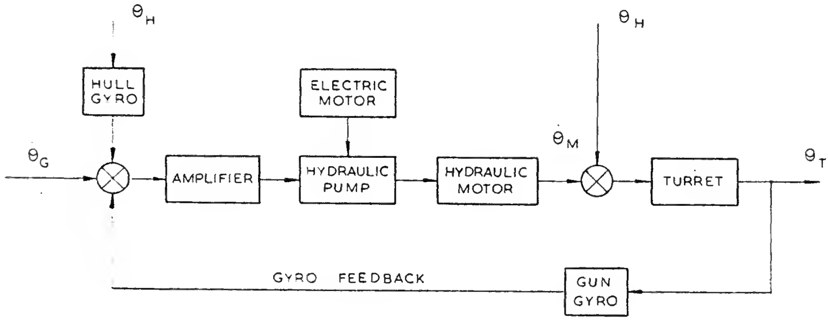


Fig. 8.2 Simplified block diagram of an electro-hydraulic traverse drive with gyro feedback and an open-loop feedforward channel.

errors which are left to be dealt with by closed-loop feedback action. In fact, attenuation of as much as 80 to 85 per cent of the effects of hull yaw and turret pitch has been recorded (8.15). As a result, the addition of feed-forward control increases significantly the overall accuracy of stabilisation systems.

To provide appropriate feed-forward signals, two gyroscopes are used. One of them is mounted in the hull to sense its angular velocity in the plane of the rotation of the turret and a simplified block diagram of an electro-hydraulic traverse drive incorporating an open-loop feed-forward channel is shown in Fig. 8.2. The second gyroscope is mounted in the turret to sense its angular velocity in the elevation plane of the gun.

The use of feed-forward control was pioneered by the Cadillac Gage Company, following the revival of interest in stabilisation in the United States in the late 1950s. In particular, it was incorporated in the Cadillac Gage 'Add-On' stabilisation system, which was first demonstrated in 1962 and which was adopted in 1969-1970 by the German and Belgian Armies for retrofitting their Leopard 1 tanks. Feed-forward loops have been incorporated since then in other tanks, including the Leopard 2 and the US M1, and even in the US M2 Infantry Fighting Vehicle.

Feed-forward loops have also been used in Soviet T-55 and T-62 tanks. But in their case the two primary closed loops incorporate rate integrating gyroscopes, instead of the rate gyroscopes which are generally used elsewhere, and rate integrating gyroscopes are also used in their open loops. The advantage of using rate integrating gyroscopes is that they provide a memory of the gun position, so that the gun is driven back by the control system to its position before any disturbance no matter how severe the latter might be, which is not the case with control systems using rate gyroscopes.

A further refinement incorporated in some of the more recent stabilisation systems is the addition of yet another rate gyroscope, to sense the roll of the turret. In other cases, including the Cadillac Gage 'Add-On' system, the gun azimuth gyroscope is mounted so that it senses the turret roll rate, as well as the turret azimuth rate, and together with the gun elevation gyroscope it can therefore provide signals for vehicle roll compensation as well as azimuth compensation.

Some of the more recent stabilisation system also incorporate accelerometers,

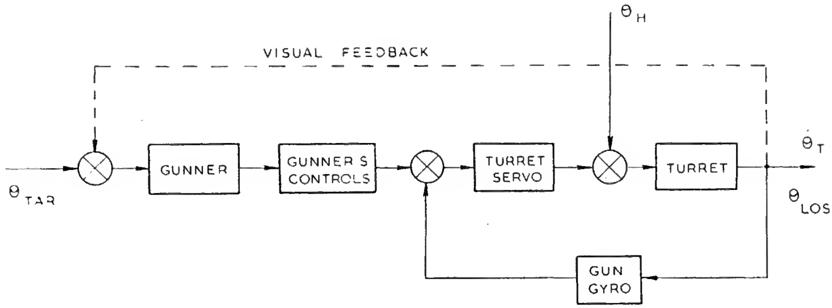


Fig. 8.3 Simplified block diagram showing the function of the gunner in closing the target to line-of-sight loop:
$\dot\theta_{TAR}$ = *target azimuth rate*
$\dot\theta_{LOS}$ = *line-of-sight azimuth rate*

especially to measure the angular acceleration of the turret in azimuth, in order to produce signals which result in the artificial damping of mechanical resonances.

The outcome of all the refinements incorporated in the second-generation systems has been to reduce considerably gun-pointing errors and consequently to increase further the probability of hitting targets on the move. The improvements are characterised by a reduction in the standard deviation of the motion-induced gun-pointing errors from about 1 mil to 0.5 mil, in each axis, under typical conditions of tank operation over rough ground.

However, second-generation systems still only maintain the position of the tank guns in space and they do not provide gunners with all the aids which are possible. In particular, the gunners still have to track targets or, in other words, close the overall weapon-target loop by visual feedback, as indicated in Fig. 8.3.

8.4 Stabilised Sights and Director-Type Systems

Whenever simple stabilisation systems have been used and in several of the more elaborate gun and turret stabilisation systems the gunner's sight has been mechanically linked, or 'slaved', to the gun. In consequence, it has been stabilised to exactly the same degree as the gun. This has reduced the motion of the image presented by the sight to the gunner and has helped him, therefore, to observe on the move, which is a major practical advantage of using even simple gun stabilisation systems.

However, the response bandwidth of systems used to stabilise guns and turrets is restricted by their large inertia and it does not extend to the higher frequencies at which disturbances arise while tanks are moving. They can not therefore respond effectively to the high frequency disturbances and when the sights are mechanically linked to the guns these disturbances cause image jitter. The latter reduces the resolution of the sight and the lower quality of the image which the sight provides degrades the ability of the gunner to detect and to identify targets.

To improve the stability of the images the gunner's sight needs to be decoupled from the gun and stabilised independently. This implies the stabilisation of a mirror in the head of what is generally a periscopic sight, which is accomplished by mounting the mirror on a two-axis gimbal structure and controlling its position in

elevation and in azimuth by means of two rate integrating gyroscopes mounted within the sight. The inertia of the mirror is very small, of course, and the servo system controlling it can be of low power and wide bandwidth, which means that it can be stabilised much more accurately than the gun and the turret. In fact, the standard deviation of line-of-sight errors which exist with independently stabilised sights is only 0.1 mil or less in each axis.

The high degree of line-of-sight stability achieved with independently stabilised sights raises the quality of the images which are provided by them and this, in turn, gives gunners a chance to detect targets more quickly and at longer ranges. Independently stabilised sights also make it possible to track targets more accurately, which increases hit probability. Moreover, the accuracy with which the line of sight is stabilised makes it possible to use it as an inertial reference for the gun and the turret, instead of the inertial sensors mounted on them. In fact, this is done whenever an independently stabilised sight is used and the gun and turret are then slaved to the sight, which results in a director-type fire control system. A simplified block diagram of the traverse part of such a system with an independently stabilised gunner's sight and with the turret slaved to it is shown in Fig. 8.4.

The slaving of the gun and turret to an independently stabilised sight has not resulted in the elimination of the gun and turret feedback systems with their gun-mounted gyroscopes or, where feed-forward control is used, of the additional turret and hull gyroscopes. These have continued to be used to stabilise the guns but, since they can not do it to the high degree of accuracy to which the sight can be stabilised, there are errors between the position of the gun and the offsets from the line of sight required by the fire control system. However, the errors can be measured and the signals generated by them can be used to drive the gun into coincidence with the required offset position, increasing the accuracy with which the gun is pointed.

A further advantage of using an independently stabilised sight and slaving the gun to it is that the gun can be inhibited from firing if the error between its position and the offset from the line of sight required by the fire control system exceeds a

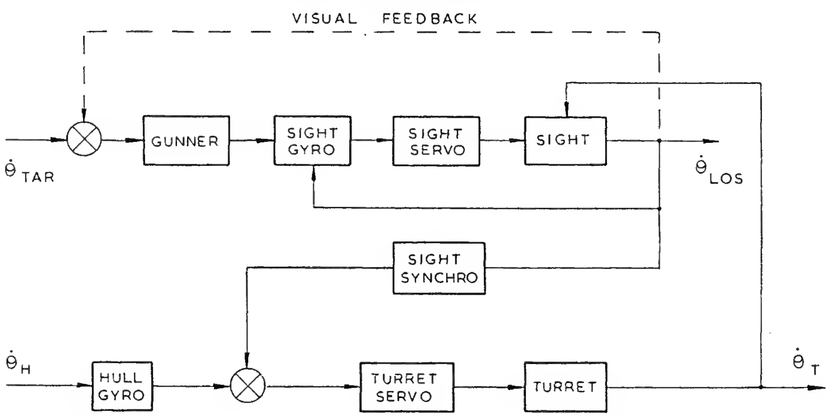


Fig. 8.4 Simplified block diagram of a director-type system with an independently stabilised gunner's sight and the turret/gun slaved to it. The gun offset command input from the fire control computer has been omitted, for the sake of clarity.

certain value. Firing under such conditions is called coincidence firing and this technique increases the probability of hitting targets by truncating the spread of gun pointing errors so far as firing is concerned.

Yet another advantage associated with independently stabilised sights is that gun offsets commanded by a fire control computer do not disturb the line of sight and, therefore, the gunner's aim. This is not the case with other sights with which the introduction of angular offsets between the gun and the sight requires the offsetting of the sight, or at least of the sight's aiming mark or graticule. The sight with such a disturbed aiming mark then has to be repositioned by elevating the gun and rotating the turret. The amount of repositioning which has to be done by the gunner can be minimised by using the sight offset rates to drive the gun and turret in the opposite sense but even if this is done some final adjustment of the aim is still required.

An independently stabilised gunner's sight was used for the first time in the mid-1960s in the US-German MBT-70 as part of a director-type fire control system developed for it by Delco Electronics. Extensive tests with the MBT-70 and subsequently with its modified XM-803 version demonstrated clearly that very accurate stabilisation could be achieved with such a sight. Thus, cross-country tests with the XM-803 at speeds of up to 32 km/hr showed that the standard deviation of the line of sight errors was no more than 0.05 mil in both elevation and azimuth. Tests with the XM-803 also showed that at speeds of up to 40 km/hr the gun pointing errors did not exceed 0.2 mil in elevation and 0.4 mil in azimuth (8.16).

A system similar to that tried in the XM-803 was subsequently developed by Delco Electronics for the General Motors prototype of the US XM-1 tank. On the other hand, the Chrysler version of the XM-1, which was adopted by the US Army and produced by General Dynamics as the M1 tank, has had a gunner's sight independently stabilised only in elevation. In azimuth the sight relies on the stabilisation of the turret but the aiming mark, or graticule, is driven in azimuth by a separate servo system so that its motion as observed by the gunner is minimised. At the same time the turret is pseudo-directed in azimuth to its proper aiming angle while the gun is controlled in elevation as in a director-type system.

This hybrid system was adopted by Chrysler on the grounds that the contribution of errors in azimuth to the overall accuracy of a stabilised weapon system was only one third of the contribution of the errors in elevation. In consequence, it was not considered cost effective to provide independent stabilisation for the gunner's sight in azimuth as well as elevation and it was argued that the stabilisation of its head mirror only in elevation would make the sight not only simpler and less expensive to produce but also more robust. In fact, the sight system of the M1 tank is, if anything, more complex than that of sights independently stabilised about both axes and its performance characteristics are, inevitably, inferior to theirs in some respects.

A much simpler alternative to the director-type systems has been developed in Sweden by Bofors Aerotronics and in Britain by Marconi Command and Control Systems in the form of a pseudo-director system. With this system the sight remains slaved to the gun but the injected aiming mark, or graticule, is decoupled from it and stabilised. In consequence, when the gunner aims at a target he only drives the aiming mark. However, while he is laying the aiming mark on the target the fire control computer compares the position of the aiming mark with that of the gun and commands the appropriate gun offsets.

The advantage of the pseudo-director system is that it provides a highly

stabilised aiming mark without the cost and complexity of an independently stabilised sight and can be applied readily to existing tanks with simple telescopic or periscopic sights mechanically linked to tank guns. In fact, Bofors Aerotronics produced their system, from 1983 onwards, for retrofitting Centurion tanks. Unfortunately, the pseudo-director system does nothing to improve the stability of the image which the gunner sees. It does nothing, therefore, to improve his ability to detect and to identify targets on the move, which he needs to do in the first instance.

Because of the shortcomings of the alternatives, several more recently designed tanks have followed the example of the MBT-70 in having director-type fire control systems with a gunner's sight independently stabilised in azimuth as well as elevation. They include the Leopard 2 and, more recently, the South Korean Type 88, the Osorio developed by Engesa, the Italian C-1 Ariete and the Japanese TK-X.

Leopard 2, as well as the others, also has in its fire control system coincidence firing limits, to reduce motion-induced firing errors. It is not however the first tank to go into service with them. Coincidence firing was first adopted in the mid-1960s in the turretless Swedish S-tank, which has a rudimentary director-type fire control system based on a commander's cupola stabilised in azimuth and sight-stabilised in elevation. But in the case of the S-tank the coincidence firing limits have only been imposed in elevation.

Another refinement which has accompanied the development of director-type systems is the introduction of rate-aided tracking. This represents an advance on the compensation for the angular motion of tanks which, in principle, is all that the

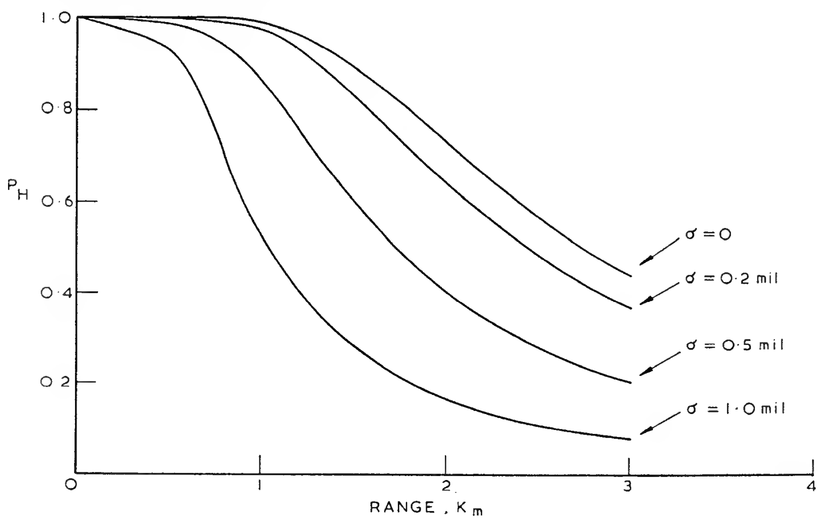


Fig. 8.5 Single shot hit probability P_H versus range for a stationary tank (σ = 0) and firing on the move with the aid of three different stabilised gun control systems:

- *basic system, σ = 1.0 mil*
- *second-generation system, σ = 0.5 mil*
- *director-type system with coincidence firing limits, σ = 0.2 mil*

stabilisation systems were intended to do until then. The introduction of rate-aided tracking means that it is no longer left entirely to the gunner to compensate for the relative translational motion between his tank and the target. In particular, rate-aided tracking compensates the direction of the gunner's line of sight for the translational motion of his own tank.

The addition of open-loop rate-aiding involves the provision of supplementary sensors in the form of accelerometers to measure the translational disturbances as well as the speed of the tank normal to the gunner's line of sight. It also involves processing of the signals, but this can be taken care of by the digital fire control computers. When rate-aided tracking is added the gunner still has to compensate, by himself, for any changes in the motion of the target. Nevertheless, it improves his performance considerably. Thus, tests with the MBT-70 and XM-803 showed that rate-aided tracking can reduce aiming and tracking errors by a factor of two.

The MBT-70 and XM-803 were actually the first tanks to incorporate rate aided tracking, which was developed for them by Delco Electronics and their example was followed by the Leopard 2, which became the first tank to go into service with it.

The relative performance of which the different stabilised gun control systems are capable is indicated in Fig. 8.5. This shows theoretical curves of single shot hit probability P_H versus range for a tank fitted with an advanced fire control system and firing high velocity projectiles at a standard 2.3 x 2.3m NATO target. The tank is either stationary or moving at speed over rough ground and using one of three different stabilised gun control systems, namely a basic system, a second-generation system and a director-type system with coincidence firing limits, which reduce the standard deviation σ of the motion-induced errors to 1.0, 0.5 and 0.2 mil in each axis respectively.

It is evident that the curve for the director-type system is very close to that for the stationary case, or what would be a theoretically perfect stabilisation system. This means that stabilised gun control systems offer the possibility of really effective fire on the move. But they do this at a price, both in terms of complexity and money.

8.5 References

8.1 *Movement and Firepower*, Royal Armoured Corps Tank Museum, Bovington Camp, 1965, p.26.

8.2 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, pp.34 and 43.

8.3 *Instruction sur l'Armement et le Tir dans les Unites de Chars Legers*, Charles-Lavauzelle, Paris, 1937, pp.75 and 93.

8.4 W Esser, *Dokumentation über die Entwicklung und Erprobung der ersten Panzerkampfwagen der Reichswehr*, Krauss-Maffei, Munich, c.1979, pp.24 and A.5.5.

8.5 J Bingham, *French Infantry Tanks*, AFV/Weapons Profile No.58, Profile Publications, Windsor, 1973.

8.6 D Crow and R J Icks, *Encyclopedia of Tanks*, Barrie and Jenkins, London, 1975, pp.62 and 220.

8.7 J Milsom, *Russian Tanks 1900-1970*, Arms and Armour Press, London, 1970, p.56.

8.8 J W Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, p.153.

8.9 R Hacker, 'Neue Taktik mit neuen Türmen?', *Wehr und Wirtschaft*, No.10, October 1974, pp.437-440.

8.10 R N Evans, 'Chieftain Gun Control Equipment', *The Engineer*, Vol.218, No.5662, 31 July 1964, pp.170-171.

8.11 R Hunnicutt, *Patton*, Presidio Press, Novato, 1984, pp.47, 74, 114 and 134.

8.12 F. Garner, *The Design of Gun Control and Stabilization Systems for Future Armoured Fighting Vehicles*, High Technology in Defence Symposium, Brighton, 1981.

8.13 *Cromwell I Service Instruction Book*, Chilwell Catalogue No.62/372, 1943.

8.14 *La Tourelle FL 11*, Ecole d'Application de l'Arme Blindé et de la Cavalerie, Saumur, 1960.

8.15 A Henry, 'Precision Weapon Stabilization Enables Fire-on-the-Move', *Defense Systems Review*, October 1984, pp.56-59.

8.16 *Integrated Small Craft Weapon System*, Delco Electronics, Santa Barbara, 1975, pp.22-25.

Chapter 9

Guided Weapons

9.1 Development of Anti-Tank Guided Missiles

The development of anti-tank guided missiles is commonly thought to be entirely adverse to tanks and in the extreme to threaten their existence. In fact, it has also been of some benefit to tanks in producing an alternative, or supplement, to their gun armament.

As an alternative to tank guns, guided missiles offer the advantage of light weight and of high accuracy. They consist, in effect, of rockets which can have powerful warheads but with which there are practically no recoil forces, so that they can be installed on relatively light vehicles. Since they are guided, they also offer a high probability of hitting targets, in contrast to unguided rockets which are not competitive in this respect with guns.

Moreover, instead of threatening the existence of tanks the development of anti-tank guided missiles has created an additional demand for tank-like and other, if only light-weight, armoured vehicles because the more powerful of the missile systems need to be mounted in them if they are to have an adequate degree of battlefield mobility and if they are to be, therefore, fully effective.

The development of anti-tank guided missiles began in Germany in 1943 (9.1). Its original outcome was the X-7 *Rotkäppchen*, a winged missile with a two-stage solid-propellant rocket motor and a flight velocity of 98 m/s, which could be guided to a range of 1200m by signals transmitted through a trailing wire link. It had a 140mm diameter body with a shaped charge warhead and a launch mass of 9kg.

The X-7 began to be produced in 1945 but work on it was brought to an end by the defeat of Germany. However, in 1946 the development of the X-7 type of missile was taken up in France, at what was then the Arsenal de l'Aéronautique. It bore fruit six years later in the production of the SS-10, which became the first operational anti-tank guided missile in the world.

Like its German forerunner, the SS-10 had a solid propellant rocket motor and relatively low flight velocity of 80 to 90 m/s. It was guided through a trailing twin-wire link to a range of 1600m and its launch mass was 15kg. The diameter of its body was 164mm and the shaped charge warhead it contained was capable of penetrating 400mm of armour.

The SS-10 continued to be produced until 1963, by which time 29 850 had been made not only for the French but also for the US Army. The SS-10 was superseded by the ENTAC, or *Engin Teleguidé Antichars*, which was similar in principle but had a smaller wing span of 375mm and a more effective shaped charge warhead

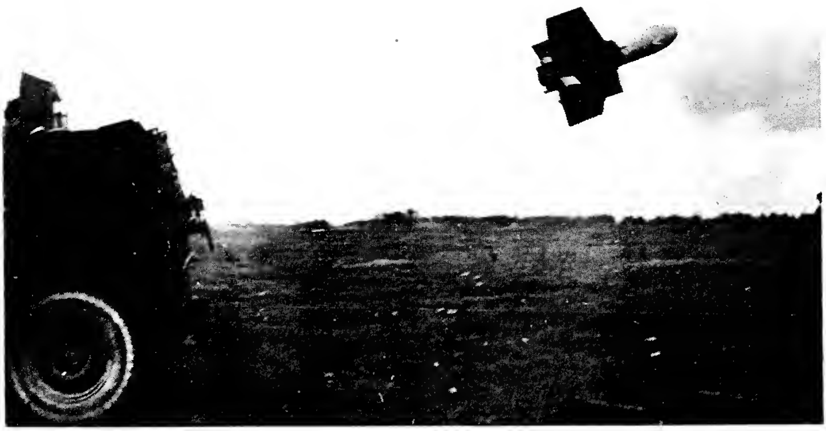


Fig. 9.1 SS-10, the first anti-tank guided missile to come into service. (Nord-Aviation)

capable of penetrating more than 650mm of armour, even though it had a smaller, 150mm diameter body.

Both the SS-10 and the ENTAC were mounted on jeeps but they remained essentially infantry anti-tank weapons and were not mounted on armoured vehicles. The first to be mounted on armoured vehicles was another *Sol-à-Sol* missile developed in France, the SS-11, which became operational in 1956 and was eventually adopted by more than 20 different countries. The SS-11 was very similar to the SS-10 but had a higher average flight velocity of 160 m/s and a longer range of 3000m. With a mass of 29.9kg at launch the SS-11 was also heavier and although its body had the same diameter of 164mm as the SS-10 the 125 or 140mm shaped charges it contained could perforate 625 to 660mm of armour under static firing conditions.

This meant that the SS-11 had the armour piercing capabilities as well as the range required of the armament of tanks. But, like other first-generation missiles, it suffered from a number of serious disadvantages. The principal one was its dependence on the performance of a human operator, due to the fact that it was, in effect, a miniature rocket-propelled aircraft which had to be piloted, by remote control, on to the target. This required a high degree of skill on the part of the operator and to develop it extensive training.

The missile operator's task was eased somewhat in the first-generation anti-tank missiles produced during the 1960s in Britain, such as the Vigilant and the Swingfire, which incorporated an autopilot. In consequence, they had a velocity, instead of an acceleration, control system which simplified the operator's task of guiding them on to their targets. Nevertheless, like the other first-generation missiles, they still demanded a very high degree of concentration on the part of the operator during their flight to the target, which could last 20 seconds, and this is not easy to achieve on the battlefield. As a result, the chances of hitting targets with the first-generation missiles were considerably lower under battlefield conditions

than they were at peace-time demonstrations, where hit probabilities of 90 per cent were being achieved.

The first time that anti-tank guided missiles were actually used on the battlefield was in 1965, during the fighting between India and Pakistan. The missiles were the BO 810 Cobras, which were very similar in principle to the SS-10 but produced in Germany by the Bölkow company, and which were employed without much success by the Pakistani troops against Indian tanks.

It was only eight years later, during the 1973 Arab-Israeli war, that anti-tank guided missiles scored their first major success. The missiles in this case were the Soviet-made, first-generation 9M14M or PUR-63, code-named 'Sagger' by NATO, which were used with considerable although often exaggerated success at the crossing of the Suez Canal by the Egyptian infantry against the initial counter-attacks by Israeli tank units.

In the meantime the shortcomings of the first-generation missiles with their manual command to line of sight (CLOS) guidance led to the development of semi-automatic command to line of sight (SACLOS) guidance. This still required the missile operator to track a target manually but absolved him of the task of simultaneously tracking the missile, which was now done automatically.

The lead in this development was taken by Nord-Aviation, the producers of the SS-10, ENTAC and SS-11, who in 1962 developed the *Télécommande Automatique*, or TCA for the SS-11. The latter was based on the use of an infrared sensor, or goniometer, aligned with the operator's optical system to track the tracer flare at the back of the missile and to measure its deviation from the operator's line of sight. The error signals were then fed into an electronic computer which sent commands through the trailing wire link to steer the missile within a 1 metre radius of a line parallel with the line of sight. In consequence, TCA reduced the operator's task to placing the cross-hairs of his sight on the target and keeping them on it during the missile's flight. This eliminated much of the skill and training previously required by missile operators and, because it made their task much

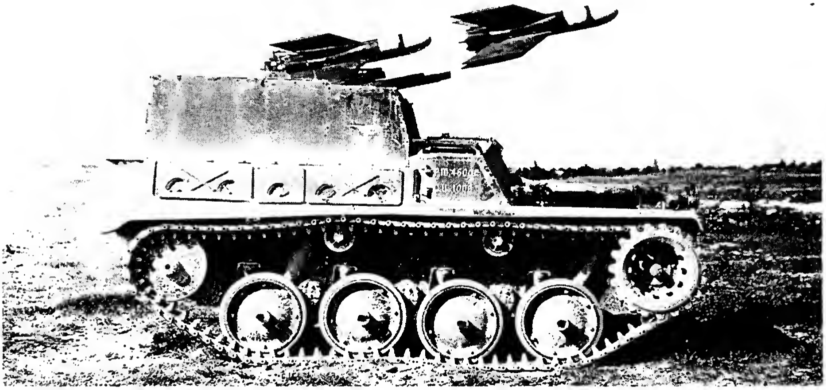


Fig. 9.2 SS-11 launched from one of its earliest installations on an armoured vehicle – a Hotchkiss light carrier.

simpler, it has helped to improve hit probability. The automatic sensing of errors between the line of sight and the position of the missile also improved the response of the missile system, making it better able to engage rapidly moving targets and reducing the minimum distance at which targets could be engaged.

Although the use of the TCA with the SS-11 missiles represented a major advance in the performance of anti-tank guided missile systems, they became even more effective when SACLOS guidance was combined with missiles more advanced than the SS-11. One notable example of such second-generation missiles is the HOT developed since 1963 by Nord-Aviation in collaboration with Messerschmitt-Bölkow-Blohm to a Franco-German requirement for a long-range anti-tank missile system suitable for installation in armoured vehicles.

The HOT system incorporates guidance similar in principle to TCA but as its name – which is an acronym for *Haute subsonique Optiquement Têléguidé* – implies its missiles have a considerably higher flight velocity than the earlier missiles and they are also less bulky. In fact, their flight velocity is 240 m/s, which would be hardly practicable with manual CLOS guidance and which makes for a significantly shorter time of flight to the target. The overall length of a HOT is not very different from that of the SS-11, but, instead of the fixed and relatively large-span wings or fins of the SS-11 and other first-generation missiles, it has folding fins, and therefore fits into a tube with an outside diameter of 175mm. This is comparable to the diameter of the cartridge case of 120mm tank ammunition and makes it much easier to use HOT missiles in armoured vehicles.

The tube of resin-bonded glass fibre is 1.3m long and acts as a launcher as well as a storage container. The launching of missiles from such tubes and the use of SACLOS guidance reduced the minimum target engagement range of HOT missiles to 75m, compared with 300 to 400m of the SS-11. At the same time their maximum range increased to 4000m, in spite of the fact that they continue to rely on a trailing wire command link. Their armour-piercing capability is also greater than that of the earlier missiles. Thus, the 136mm diameter shaped charge warhead of the original HOT missiles can perforate more than 800mm of armour while the 150mm warhead of HOT-2, introduced in 1985, can perforate as much as 1300mm of armour.

Another notable example of a second-generation anti-tank guided missile system with SACLOS guidance is the TOW developed in the United States since 1961 by the Hughes Aircraft Company. The TOW system with its BGM-71 missile was adopted by the US Army in 1968 and between then and mid-1985 more than 350 000 of its missiles were produced for the armed forces of some 35 different countries.

Its name, which is an acronym for Tube-launched Optically-tracked Wire-guided, gives a good indication of its general characteristics. Thus, a TOW missile is contained, ready to launch, in a sealed tube which is 1.27m long and has an outside diameter of 200mm. Like HOT, TOW has a two-stage rocket motor but whereas the second, sustainer stage of HOT's motor maintains its flight velocity practically constant at 240m/s throughout the flight, the second stage of TOW's motor accelerates it to a maximum of about 300 m/s within two seconds of launch and then burns out, leaving the missile to coast the rest of the way. This reduces the smoke and thermal signatures of the missile and the time of flight at relatively short ranges but increases it somewhat at long ranges.

Conceived as an infantry anti-tank weapon, TOW originally had a maximum range of only 2000m but this was subsequently increased to 3000m and then to 3750m, while its minimum range remained at 65m. TOW's warhead has had a

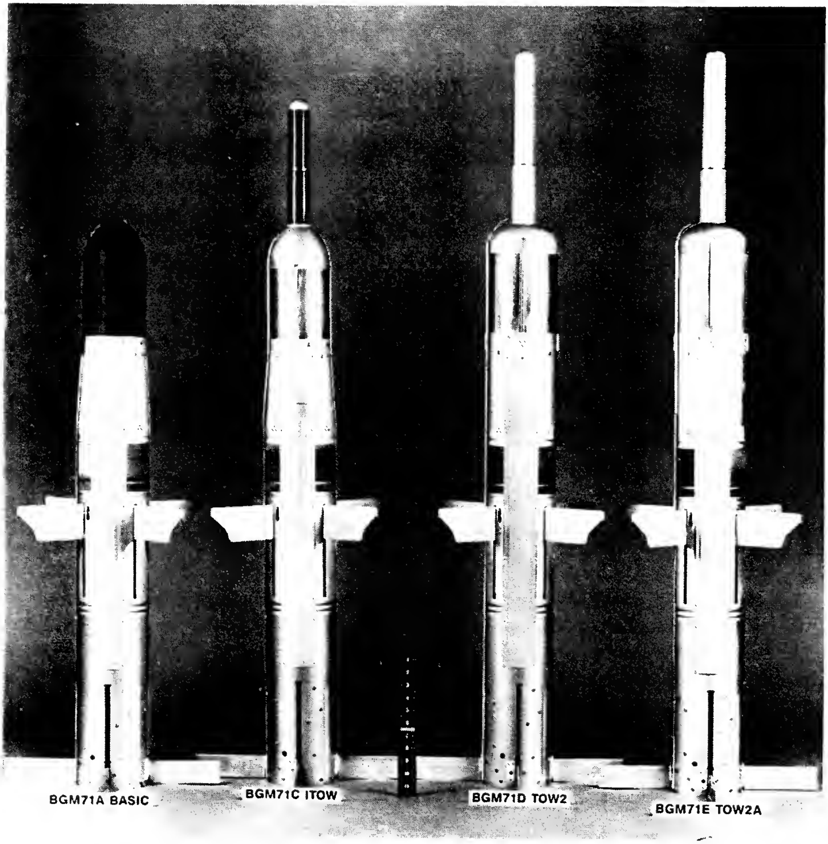


Fig. 9.3 Successive versions of the TOW missile: from left to right, original TOW with 127mm warhead, improved TOW with telescopic probe for detonation at greater stand-off, TOW 2 with 152mm warhead and TOW 2A with a small precursor warhead in the nose for detonating explosive reactive armour in advance of the main warhead. (Hughes Aircraft Co.)

diameter of 127mm and was originally capable of penetrating 530mm of armour at optimum stand-off distance. However, its armour piercing capability was subsequently increased and with TOW 2, which was introduced in the mid-1980s, the diameter of the warhead was enlarged to that of the missile body, namely 152mm.

9.2 Guided Missiles versus Tank Guns

The development of missiles such as HOT and TOW made the second generation of anti-tank guided missiles much more competitive with tank guns as a means of killing enemy tanks and, consequently, as the main armament of tanks. Their principal advantage was perceived to be their higher hit probability, particularly at

longer ranges when the hit probability of tank guns falls to low values. In fact, the hit probability of HOT against standard targets was at one stage claimed to be approximately 80 per cent at up to 500m and "close to 100 per cent for the rest of its range" (9.2). Information subsequently published about HOT firings showed that of the total of 6892 missiles fired 86.7 per cent hit their targets and that the percentage went up to 90.9 per cent when missiles which did not function correctly were excluded (9.3). Similar results have been obtained with TOW. Thus, according to information released by the Hughes Aircraft Company, of more than 1000 TOW missiles fired in US Army trials 96 per cent hit standard 2.3m × 2.3m targets at a range of 3000m and of a total of 10 500 TOW firings throughout the world 83 per cent resulted in targets being hit.

The hit probability achievable with second-generation missiles is clearly high but any assessment of them in relation to tank guns must also take into account their reliability, which has a significant impact on the percentage of missiles that actually hit targets. Considering the relative complexity of missile systems their reliability has been high. Thus, the manufacturers of the SS-11 already guaranteed, by contract, an operational reliability of 93 per cent and a reliability of 95.2 to 96.2 per cent has been demonstrated by the firings of HOT while the reliability of TOW has been quoted at 93 to 96 per cent on the basis of more than 10 000 firings (9.4, 9.5). Nevertheless, in spite of being relatively high, reliability has to be taken into account when comparing missiles with guns.

When this is done, the hit probability of first and second generation missile systems and of tank guns firing APDS projectiles with the aid of simple and advanced fire control systems varies with range as shown in Fig.9.4. This illustrates that missiles of either generation have a considerably higher hit probability than guns at long ranges. But at short ranges the position is reversed and it is at relatively short ranges that most engagements are likely to take place. The reason

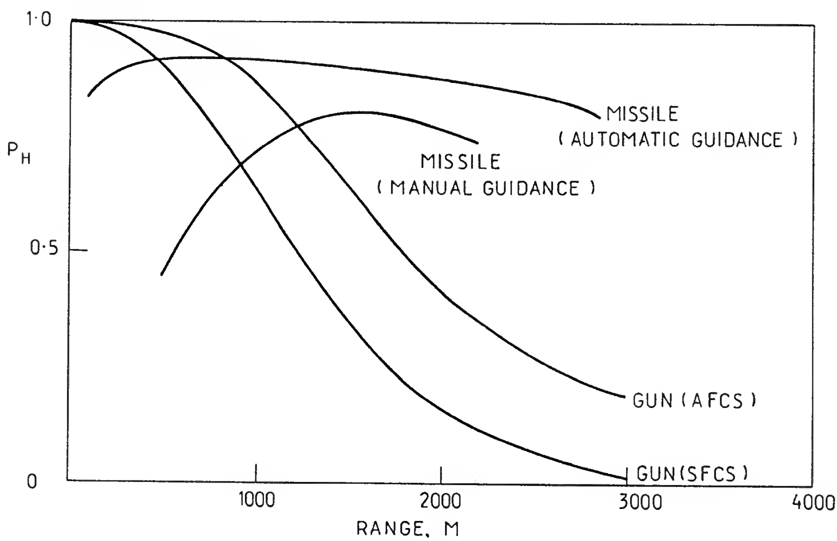


Fig. 9.4 Comparison of hit probabilities of missiles with manual and automatic guidance and of guns with simple and advanced fire control systems.

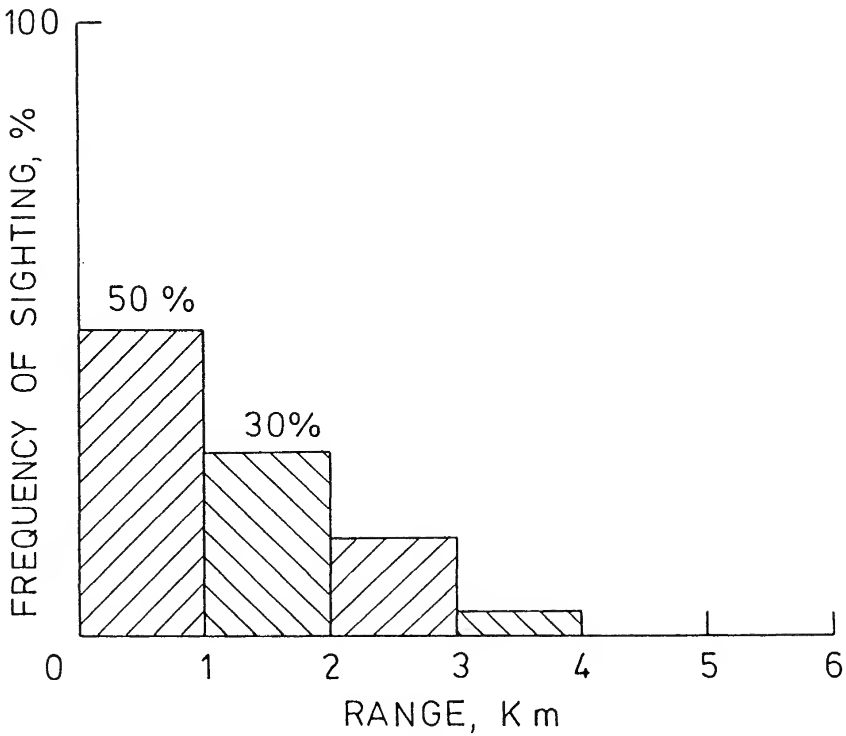


Fig. 9.5 Histogram of the frequency of sighting targets in Central Europe.

for it is the nature of the terrain which results in a frequency of sighting of targets illustrated by the histogram of Fig.9.5. The histogram indicates that in Central Europe 50 per cent of the targets are likely to appear at 1000m or less, and within much of this range guns have a higher hit probability than even second-generation missiles.

Moreover, single shot hit probability is not the ultimate measure of the relative effectiveness of gun and missile systems (9.6). A more comprehensive and valid measure of it is the time that it takes to hit a target, which involves not only hit probability but also the rate at which targets can be engaged. When this is taken into account the range at which missiles begin to have a shorter time to hit than guns and are, therefore, superior to them becomes greater than the range at which their hit probability curves cross over, as shown diagramatically in Fig.9.6. This is due to guns being able to deliver aimed fire at the rate of about 8 rounds per minute, whereas missile systems can only engage targets at half that rate at best. In consequence, the majority of engagements are likely to occur within the range up to which guns are more effective.

In addition, second-generation missiles have proved to cost, on average, approximately twenty times as much as rounds of armour piercing tank gun ammunition. Another disadvantage of missiles has been that if they were adopted as tank

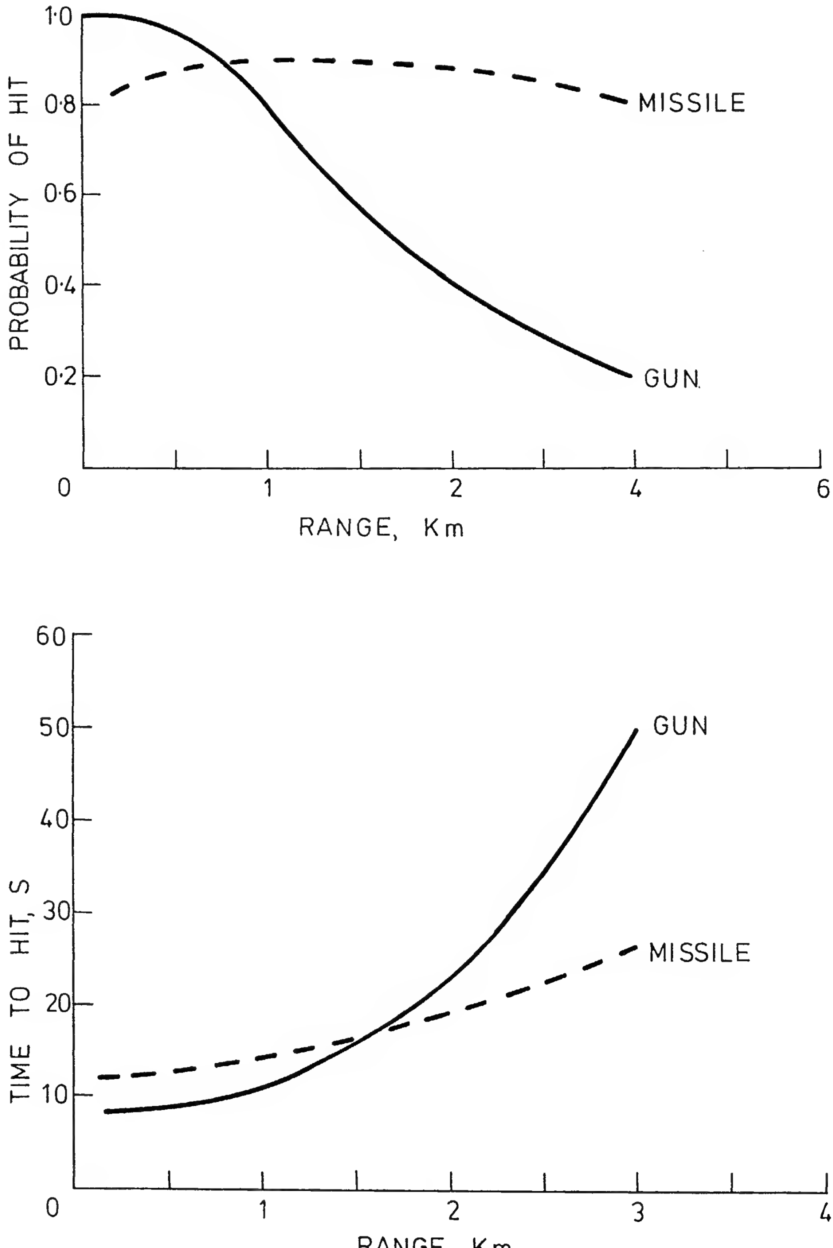


Fig. 9.6 (a) and (b) Comparison of the hit probability (a) and of the time to hit (b) versus range of guided missile and gun systems.

armament the enemy would have been able to optimise the protection of his tanks against the only form of attack which they could deliver with their shaped charge warheads, instead of having to protect them also against kinetic projectiles.

All this led to the view that guided missile systems do not represent an effective alternative to guns as the armament of the majority of tanks. The only tanks or tank-like vehicles that can be more effectively armed with guided missiles are those expected to exploit the infrequent opportunities of engaging targets at long range and only relatively small numbers of them are justifiable.

This view remains valid even in the light of the development of the third generation of anti-tank guided missiles. These are bound to overcome some of the disadvantages of the second-generation missiles but others will remain, as they are inherent to missile systems. In particular, from the point of view of their use in tanks, guided missiles suffer from the disadvantage of being relatively bulky as well as complex and costly.

One of the disadvantages that can be overcome is the low flight velocity of missiles. This can be done by removing the restrictions imposed by the use of the trailing wires by replacing them by a very short wave radio or, more effectively, a laser beam command link. Alternatively, SACLOS guidance can be abandoned altogether in favour of laser beam-riding guidance. The latter has been adopted for the Oerlikon Air-Defence Anti-Tank System (ADATS) developed since 1975, which uses a coded CO_2 laser guidance beam and whose missiles attain a flight velocity of more than 1050 m/s.

Beam-riding requires a missile to carry a rearward-facing receiver to measure the angular deviations of its position from the axis of the guidance beam and to process them by its on-board guidance electronics in order to produce correction commands which keep the missile properly positioned within the beam. The projector of the laser guidance beam is colimated with the sight, so that the missile is, in effect, guided automatically along the line of sight and the operator only has to track the target, as he does with SACLOS guidance systems. However, a beam-riding guidance system is simpler because there is no need with it for a missile tracker. On the other hand, its guidance beam can be detected at the target in advance of the arrival of the missile and, in theory, this lays it open to countermeasures. But with a high velocity missile there is not likely to be enough time for the countermeasures to be effective.

A disadvantage which remains with beam-riding as well as SACLOS guidance is that the operator still has to track the target during the whole of the missile's flight, which with targets at long range can require a significant period of time. During that period his aim can be disturbed by various events, including enemy fire, and he can not launch another missile until it is over, which slows down considerably the rate of target engagement.

All this can be overcome by going over to homing guidance systems, which involve missiles carrying their own target trackers or seekers. Given such a system, the operator need only lock on to a target before, or even after launch, after which the missile flies on to the target by itself. When this happens the use of guided missiles becomes a matter of 'fire-and-forget', as it is with guns.

Homing guidance systems are based on seekers which can detect the radiation emitted or reflected by targets, discriminate between them and the background and generate guidance signals for missile homing. In the first case it is generally thermal radiation which is detected, by means of a passive infrared seeker. In the second case the radiation can come from and on reflection is detected by an active millimetre wave seeker. When semi-active systems are involved, the radiation can

also come from a laser target designator separate from the missile and on being reflected from the target is detected by a laser seeker in the nose of the missile. Dual mode seekers are also being developed in order to exploit the complementary performance characteristics of infrared and millimetre wave seekers and thereby make homing systems better able to cope with different weather conditions and with countermeasures.

Missiles with homing guidance are more complex, of course, and more costly than those with SACLOS or beam-riding guidance. However, they offer a greater probability of hitting targets at long range and their employment for this purpose is considered justifiable.

9.3 Installation of Guided Missiles in Armoured Vehicles

The installation of guided missiles in armoured vehicles began in the mid-1950s with the SS-11. In particular, the French Army started to examine the mounting of SS-11 on the AMX-13, which made it much more effective as a tank destroyer than it was in its original form armed only with a 75mm gun. In fact, the AMX-13 with SS-11 was considered so effective as a long-range tank destroyer that under the 1959 organisation of the French armoured units a squadron of twelve was included not only in each four-squadron regiment of AMX-13 but also in each battle tank regiment.

Nevertheless, the installation of the SS-11 on the AMX-13 was of a makeshift

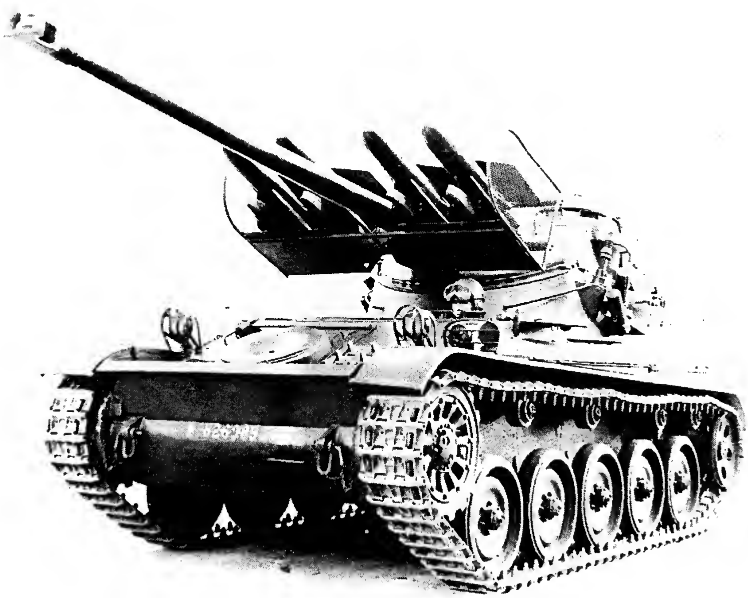


Fig. 9.7 SS-11 missiles mounted on the turret of an AMX-13 light tank. (French Army)

nature with the missiles mounted on the front of the turret, two on each side of the 75mm gun. In consequence, the missiles were vulnerable to damage by bullets and shell fragments or even to being struck by the branches of trees. However, the size of the SS-11 missiles and in particular the span of their fins made an external installation unavoidable and limited the number of missiles per vehicle to four. But, for all this, the mounting of the SS-11 on the AMX-13 represented the first operational installation of guided missiles on a tank.

The AMX-13 with the SS-11 actually entered service with the French armoured units in 1964, at which time it still relied on manual CLOS guidance (9.7). But in 1970 the French Army decided that it should be fitted with TCA, that is with SACLOS guidance, which, of course increased considerably its effectiveness. The AMX-13 would have become even more effective had the SS-11 been replaced by HOT missiles when these appeared. But although the installation of HOT on the AMX-13 was studied in the mid-1960s and was much neater than that of the SS-11, consisting as it did of a three-missile pod on each side of the turret, its development did not proceed beyond the prototype stage.

In the mid-1960s the British Aircraft Corporation also proposed the external installation of its Swingfire missiles on at least three different tanks but none of the proposals proceeded beyond mock-ups. Thus, the AMX-13 with the SS-11 remained the only tank in service with guided missiles as a complementary form of tank armament.

But although the example of the AMX-13 was not followed by other tanks, the use of missiles as a complementary or supplementary form of armament was adopted in the mid-1960s on the Soviet BMP infantry armoured vehicle. In this case only one 'Sagger' missile was mounted on the outside of the turret, above its 73mm gun, but four additional missiles were carried inside the vehicle. In 1976 the US Army also decided to modify its XM723 Mechanized Infantry Combat Vehicle to carry a turret with a two-missile TOW launcher on one side of it and developed the XM723 into the M2 Infantry Fighting Vehicle, which has been produced in quantity since 1981.

Whatever its attractions, the mounting of anti-tank guided missiles on infantry vehicles is open to the very serious objection that it imposes on them the task of engaging enemy tanks which is very different and to a large extent incompatible with their basic role of carrying infantrymen. Moreover, whenever missile-armed vehicles carrying infantrymen engage in a fight with enemy tanks they place at risk many more men than if this were done by tanks or by special, missile carrying vehicles. It is much more sensible, therefore, to refrain from mounting anti-tank guided missiles on armoured vehicles carrying infantrymen and to mount them instead on special vehicles. The latter may be modified versions of the infantry armoured vehicles but at most they would have a crew of four, instead of carrying and risking unnecessarily up to ten men. The employment of such vehicles also avoids the conflict between the basically different roles of a missile launcher and of an infantry carrier.

In fact, most anti-tank guided missiles have been mounted on special vehicles, or rather special versions of infantry and reconnaissance vehicles. The simplest of them have had one-man turrets with one or two missile launchers on either side. An early example of this was the almost standard, machine gun turret of the British Ferret Mark 2/6 scout car which was fitted with two Vigilant anti-tank guided missiles and which was adopted by the Royal Armoured Corps in 1962 (9.8). A much more recent example of it is the one-man turret with a TOW launcher on either side, which was developed in Norway by the Thune-Eureka company and

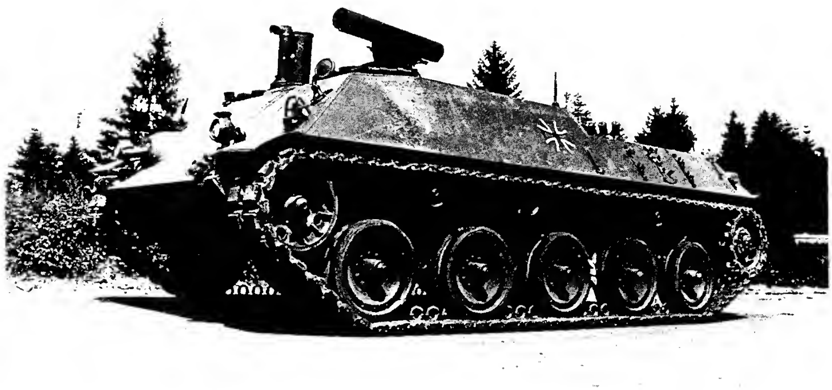


Fig. 9.8 German Jagdpanzer Rakete *with a HOT missile on its launching ramp. (Messerschmitt-Bölkow Blohm)*

which has been adopted by the Norwegian Army for installation on the M113 armoured carrier and by the Swiss Army for installation on the Mowag Piranha six-wheeled armoured carrier.

The one-man turrets generally offer the advantage of simplicity but little else and they compare unfavourably with the alternative type of missile installation introduced by the Soviet Army around 1962. Its essential feature has been the mounting of missiles on an elevatable launcher, which is normally carried within the hull and which is only raised out of it to fire the missiles. When lowered into the hull the launcher is fully protected by armour, which prevents accidental damage of the missiles and also eliminates the 'mission signature' of the vehicles as no missiles are visible.

The first to carry this type of installation was the four-wheeled BRDM-1 reconnaissance vehicle, which was fitted with a 2P26 launcher with three PUR-61 missiles, code-named 'Snapper' by NATO. To allow the launcher to be raised the roof plates were folded over the side and a similar arrangement was used in the next version, which had a launcher with four PUR-62 'Swatter' missiles. The third version has had a launcher with six PUR-63 'Sagger' missiles and in this case the whole of the roof section over the launcher moved up neatly with it in an umbrella-like mode. The same form of roof cover was also used over the four PUR-62 and six PUR-63 missile launchers installed in the BRDM-2 (9.9).

A similar approach was adopted more recently in France by Euromissile, leading to the development of the Mephisto launcher for HOT missiles, which has been adopted by the French Army for installation on its four-wheeled VAB armoured carriers. The launcher contains four HOT missiles and is raised, when the missiles are to be fired, from within the hull of the carrier together with the section of the roof which is above it. In the raised position the launcher can be traversed through 360° and on its axis of rotation is a sighting periscope with a gyrostabilised

head mirror which moves up with the launcher or which can be raised independently of it for observation. When lowered into the hull the launcher aligns with two four-missile revolving magazines from which it can be reloaded without the crew having to leave the protection of the vehicle.

A very different approach was adopted during the 1960s in Germany, where SS-11 missiles were installed in the *Jagdpanzerrakete*, or JPz 3-3, a turretless guided missile tank destroyer based on the HS-30 tracked armoured infantry vehicle. The JPz 3-3 had a commendably low silhouette and carried its missiles under armour in the centre of the hull from which they were brought out, one at a time, by one of two retractable launching posts. The JPz 3-3 was also fitted with a tall periscope over its crew compartment at the front of the hull so that it could take up firing positions behind cover showing no more than the head of the periscope and one of the missiles.

After 1967 the JPz 3-3 was replaced by the RJPz-2 which was very similar in principle but which was based on the same chassis as the then newly produced, turretless, 90mm gun *Kanonenjagdpanzer*. In consequence, it has had better armour protection and better automotive performance. The RJPz-2 was originally built to carry 14 SS-11 missiles but between 1978 and 1983 vehicles of its type were rebuilt to carry HOT missiles and were redesignated RJPz-3, or Jaguar 1. The rebuilding involved the installation on the left centre of the hull of a Euromissile K3S firing unit consisting of a vertical drum magazine with eight missiles, which are automatically extracted, one at a time, by the launching ramp located above the magazine. The magazine can be reloaded from within the vehicle which carries 12 additional missiles. Because of the automatic extraction of missiles by the launching ramp the RJPz-3 does not require a human loader, as the RJPz-2 did, but its crew still consists of four men.

A sophisticated vehicle such as RJPz-3 is inevitably expensive but it represents a far more effective way of employing anti-tank guided missiles than putting a missile launcher on a pedestal fixed on top of an armoured carrier without any protection for its operator, which is what the US Army did for several years with its TOW missiles. In fact, it was only in 1979, ten years after TOW began to be produced, that the US Army put into service an armoured vehicle with a properly designed TOW installation. The vehicle is the M901 Improved TOW Vehicle, which is still based on the M113A1 armoured carrier, but which is fitted with a rotating cupola with two hinged arms carrying a two-tube TOW launcher. In addition to the launch tubes the launcher also contains the missile operator's optics with ×2.8 and ×13 day sight channels and a thermal imaging night sight channel. Normally the launcher rests behind the cupola with its supporting arms almost horizontal but for firing it is raised above the cupola by turning the hydraulically actuated arms into the vertical position.

The launcher looks extremely clumsy but it enables TOW missiles to be fired from under armour and it can also be reloaded without the crew exposing themselves out of the vehicle. Moreover, when raised into the firing position it is 1.5m above the roof of the carrier which makes it possible for the M901 fitted with it to engage targets from behind cover without exposing itself.

The possibility of raising launchers well above the vehicles carrying them, which arises out of the virtual absence of recoil forces during the launching of missiles, has been pursued much further in Germany. The outcome of it has been the mounting of missiles on manned or unmanned platforms which can be raised to a height of 12 to 15m above the ground by means of folding or telescopic masts mounted on armoured vehicles (9.10). This enables targets to be acquired and

engaged at much longer ranges than is generally possible with more conventional missile-armed vehicles. But it requires the construction of fairly elaborate, special-purpose vehicles and where unmanned platforms are used makes it necessary to rely entirely on indirect observation and sighting through closed circuit television and thermal imagers. However, in that case the missile operator is less vulnerable as he sits in the vehicle and not in the elevated platform (9.11).

9.4 Gun-Launched Missiles

With the exception of the AMX-13, all the armoured vehicles that have been fitted with guided missile launchers have only been able to aspire to competing with tanks in the destruction of enemy tanks. In fact, they have only been built for this purpose but even if attempts had been made to extend their role beyond this they would not have succeeded because guided missiles are unsuitable or can not be justified on grounds of cost when it comes to most other targets. In particular, they are far too expensive compared with shells to be used for delivering high explosive fire, which is demanded of tanks on many occasions.

One way of overcoming this problem is to follow the example of the AMX-13 and to arm a tank with a general purpose weapon in the form of a medium calibre gun in addition to providing it with a guided missile system as its principal anti-tank weapon. This has been proposed on a number of occasions but what has been tried instead is the use of a gun for launching missiles as well as for firing projectiles.

The earliest example of this has been the US 152mm XM81 gun-launcher, which began to be developed in 1959 for what subsequently became the M551 Sheridan light tank. A similar 152mm XM162 gun-launcher was also adopted for

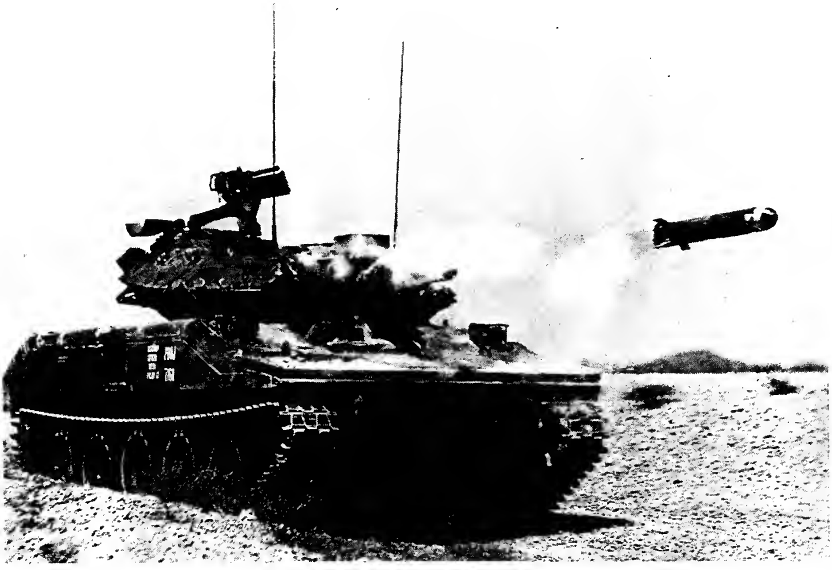


Fig. 9.9 Shillelagh missile fired from a US M551 Sheridan light tank. (Philco)

Fig. 9.10 Shillelagh missile being loaded into the turret of a US M60A2 tank.

the M60A2 battle tank and a longer barrelled 152mm XM150 gun-launcher was also developed during the mid-1960s for the MBT-70 battle tank. All three of these rifled gun-launchers could fire conventional, spin-stabilised projectiles but the XM81 and XM162 were only 17.5 calibres long and were incapable, therefore, of firing effective, high velocity, armour piercing projectiles. In fact, they were confined to firing HEAT, HE and cannister projectiles with a muzzle velocity of 683 m/s. On the other hand, the XM150 gun-launcher was 43.5 calibres long and was able to fire not only HEAT and other low-velocity projectiles but also APFSDS projectiles with a muzzle velocity of 1490 m/s.

In addition to the various projectiles, all three 152mm gun-launchers have also been able to fire Shillelagh guided missiles, which the Aeronutronics Division of the Philco-Ford Corporation began to develop in 1958. The Shillelagh antedated the TOW and HOT systems in using SACLOS guidance and it was also in advance of them in dispensing with the trailing wire link, instead of which it had an infrared command link. In its original, XM13 form Shillelagh was boosted by its rocket motor from about 80 m/s at launch to a maximum flight velocity of 320 m/s, which was only slightly higher than the maximum velocity of TOW, and its maximum range was only 2000m (9.12). But the Shillelagh's performance was improved during the course of its development so that its ultimate, MGM-51 version had a velocity of 205 m/s at launch and, although its maximum flight velocity was much the same as before, its range, against stationary targets, was increased to 3000m.

The Shillelagh represented a major step forward in the development of anti-

tank guided missiles but it was overtaken almost immediately by the missile of the French ACRA system which was also based on the use of a gun-launcher to fire missiles as well as projectiles. The outstanding feature of the ACRA, or *Anti-Char Rapide Autoguidé*, missile was that it was a beam-rider, its modulated guidance beam being provided by a neodymium-YAG laser. Its maximum flight velocity of 550 m/s was also considerably higher than that of the Shillelagh and it could reach targets at 3000m in 7 seconds, or about half the time required for it by HOT and TOW.

The gun-launcher of the ACRA system had a calibre of 142mm and was a smooth-bore, which simplified matters by comparison with the US 152mm gun-launchers where the Shillelagh had to engage with a keyway at the bottom of the barrel to prevent it being spun by the rifling. Being a smooth-bore, the 142mm gun-launcher could not, of course, fire conventional, spin stabilised projectiles. Instead, it fired a very advanced, rocket-assisted HE projectile with flip-out fins which had a muzzle velocity of 550 m/s and accelerated to a maximum of 700 m/s at 1000m. The HE projectiles as well as the ACRA missiles also had conventional, metallic cartridge cases, which avoided the serious problems experienced with the combustible cartridge cases of the projectiles fired from the US 152mm gun-launchers because of the smouldering residue they left behind.

The 142mm ACRA gun-launcher was mounted experimentally in a special turret version of the AMX-30 battle tank and in an assault gun derivative of the AMX-10 armoured carrier, the AMX-10M, three of which were built between 1969 and 1971 (9.13). But, in spite of the fact that the gun-launcher systems offered an attractive combination of the high hit probability of guided missiles with the economy of a gun, their development was abandoned in France as well as in the United States in the early 1970s in favour of high pressure guns firing APFSDS as their principal anti-tank ammunition.

However, there remains a case for firing guided missiles out of standard smooth-bore guns as a form of supplementary ammunition for the engagement of targets which are beyond the effective range of APFSDS projectiles or which are not very suitable for them, such as anti-tank guided missile vehicles and helicopters. This appears to have been accepted by the Soviet Army which, during the mid-1980s, adopted the beam-riding Kobra guided missile for firing out of the 125mm smooth bore gun of the T-64 battle tanks.

9.5 Guided Projectiles

Since the development of the Shillelagh and ACRA gun-launched guided missiles an alternative means of engaging targets at long range with tank guns has appeared in the form of guided projectiles. In principle there is not much difference between them, particularly when the guided missiles are accelerated to their maximum velocity in the first second, or so, of their flight and then coast the rest of the way, as the Shillelagh has done. However, in practice there is a considerable difference because projectiles are accelerated to their maximum velocity in the barrels of guns and, therefore, experience very much higher accelerations. For instance, the maximum acceleration of a typical 155mm artillery shell is 7200g, whereas that of a typical, second-generation anti-tank guided missile is 750g. In consequence, guided projectiles need to be much more rugged than guided missiles and their electronics in particular need to be hardened to withstand the high acceleration. This imposes weight and cost penalties, although these are offset to some extent by the absence of an on-board propulsion unit.

The most obvious choice of a guidance system for tank gun guided projectiles is the same as for gun-launched missiles. namely beamriding. But to attain a high hit probability at long range it is necessary, as with guided missiles, to resort to some form of terminal homing. The first guided projectile to be successfully developed does in fact use semi-active terminal homing. The projectile is the M712 Copperhead developed since 1971 in the Unite States by Martin Marietta for firing from 155mm howitzers (9.14). It incorporates a laser seeker which makes it home during the final part of its trajectory on to the radiation reflected from the target illuminated by a laser target designator. The use of a laser target designator implies the employment of a forward observer, which is more appropriate for the artillery than for tanks and which, even in the case of the artillery, raises questions about the effectiveness of the communication between the forward observer and the firing unit under battlefield conditions. However, if semi-active homing were used with guided projectiles fired from tanks the problem of communication could be eliminated by mounting the designator on the tanks, ideally on telescopic masts in order to extend the range at which targets could be designated. Alternatively, tank gun fired guided projectiles could use passive infrared terminal homing, which does not require any target illumination.

Whatever form of guidance is used, the provision of gun-launched guided missiles or guided projectiles could eliminate or at least reduce the need for special vehicles mounting long-range anti-tank guided missile systems, which have been considered a necessary complement to tanks. Even a partial elimination of such special-purpose missile-carrying vehicles could lead to greater tactical efficiency, because tanks with guided munitions that would take their place could not only engage targets at long range but would also be able to fight with their standard ammunition at shorter ranges which the special-purpose missile carriers can not do.

9.6 References

9.1 F Hahn, *Deutsche Geheimwaffen 1939-1945*, Erich Hoffman Verlag. Heideheim, 1963.
9.2 *HOT*, Euromissile. Paris, 1978, p.7.
9.3 *Euromissile Info 1986*, p.1.
9.4 'The TOW', *Vectors*. Vol.27, No.3. 1985, p.6.
9.5 *Airborne TOW Missile System*, Hughes Aircraft Co., Los Angeles, 1978.
9.6 B A Dunetz, 'Tank Gun or Missile?', *Armor*, Vol.82, No.2. March-April, 1973, pp.36-40.
9.7 P Touzin, *Les Vehicules Blindés Français 1945-1977*. Editions EPA. 1978, pp.80-90.
9.8 R M Ogorkiewicz. *Ferrets and Fox*. AFV/Weapons Profile No.44. Profile Publications, Windsor, 1972.
9.9 S Zaloga, *Modern Soviet Armour*, Arms and Armour Press, London. 1979, pp.58-63.
9.10 K Kuhl, 'Tank Destroyer Elevating Platform Gives Significant Increase in Combat Effectiveness of Anti-Tank Missile Systems,' *MaK Defense Journal*. No.8, December 1983, pp.22-25.
9.11 W Flume, 'The Combat Vehicle Family of the Future,' *Military Technology*, No.4, 1985, pp.76-83.
9.12 R Hunnicutt, *Patton*, Presidio Press. Novato, 1984, p.178.
9.13 P Touzin, op.cit., pp.73 and 77-79.
9.14 P H Morrison and D S Ambemtson. 'Guidance and Control of a Cannon-Launched Guided Projectile.' *Journal of Spacecraft*, Vol.14, No.6. June 1977. pp.328-334.

Technology of Tanks

II

Richard M Ogorkiewicz

JANE'S INFORMATION GROUP

Published in the United Kingdom in 1991 by
Jane's Information Group Limited
Sentinel House
163 Brighton Road
Coulsdon
Surrey CR5 2NX

ISBN 0-7106-0595-1

Distributed in the Philippines and the USA and its dependencies by Jane's Information Group Inc.
1340 Braddock Place, Suite 300, PO Box 1436
Alexandria, Virginia 22313-2036

Printed and bound in the United Kingdom by Biddles Limited
Guildford and King's Lynn

Introduction

As stated in the Preface, the object of this book is to present a comprehensive account of the technology of tanks. Its scope has, therefore, had to be extensive and in consequence its contents have run to two volumes, of which this is the second.

The first volume starts the account with an outline of the evolution of tanks to the end of the Second World War in 1945 and continues with a review of their development since then, country by country. After that most of it is devoted to the various aspects of the weapon systems which tanks serve as tracked, protected, mobile platforms. Thus, it deals with the guns which are mounted in tanks and with their ammunition and ballistics, with day and night vision and sighting systems, with fire and gun controls and with guided weapons.

This volume is concerned primarily with tanks as vehicles, which involves their mobility and automotive aspects. It begins therefore with a general discussion of the mobility of tanks and then deals with tank engines, transmissions, suspensions, running gear and soil-vehicle mechanics. The volume and the whole account of tank technology are completed with a review of the armour protection of tanks and an examination of their different configurations.

Like the first, the second volume is concerned mainly with the current state of tank technology. But is also describes earlier developments, to help the understanding of how, or why, tanks have assumed their present form.

The background of studies, lectures, writing and consulting work against which this book was written is indicated in the Preface. In it I have also mentioned some of those who have helped and encouraged me over the years in my studies of tanks but I would like to express once again my gratitude to all of them.

London 1991 *Richard M Ogorkiewicz*

Chapter 10

Mobility of Tanks

10.1 Strategic Mobility

The mobility of tanks has several different connotations as its nature varies with the scope or scale of tank operations. which results in more than one kind or level of it.

In fact, there are three clearly identifiable kinds or levels of mobility the highest of which is strategic mobility. This implies the ability of tank units to move, or be moved. into the zone of operations. Such movement generally involves considerable distances and. because of it, is not executed by tanks moving under their own power but by being transported by rail. by ships or by road transporters. The ease and speed with which this can be done are inversely related to the weight and size of tanks. So, the lighter and smaller they are the greater is the strategic mobility of tanks. Conversely. to possess a particular degree of strategic mobility tanks must keep within the weight and size limits imposed by it.

The most common method of transporting tanks has been by rail. The strategic mobility provided by it has not directly restricted the weight of tanks but it has imposed severe limits on their width. This is due to the dimensions of the existing rail bridges and tunnels and, even more, to the maximum width of the loads that trains can carry if they are to pass other trains on adjacent tracks. Thus, to enable them to be transported by rail without hindrance, tanks have been designed so that their width is within the loading gauges of the railways.

For instance. tanks designed in Britain before the Second World War were less than 2.67m wide to keep them within the loading gauge of British railways. The Berne international load gauge which applies to most of Europe allows a greater width of 3.15m for unrestricted train movement and battle tanks such as the French AMX-30 and the Swiss Pz.61 could still be designed within it. But this has not been possible with heavier tanks. To overcome the resulting problems the Tiger I heavy tank designed in Germany during the Second World War was provided with a second set of narrow tracks solely for transportation purposes. which reduced its overall width from 3.73m to 3.15m and kept it within the loading gauge. But this solution has not been adopted with other battle tanks, even though the width of most of those built since the Second World War has exceeded 3.15m.

The width of tanks such as the Leopard 2 and Merkava Mark 2 has actually reached 3.7m. But some of it is due to the skirts, particularly where they are of special armour. and these can be removed for transportation, so that no tank without them is wider than 3.5m. This is narrow enough for tank-carrying trains to

move without restrictions in Western Europe, provided that trains on adjacent tracks do not carry loads which are outside the Berne gauge.

Tanks whose width is greater than 3.5m and is not reducible to it can still be carried by rail but their transportation requires considerable planning to avoid accidents and is apt to consume much more time than the movement of tanks which can be transported without restrictions. Their strategic mobility is therefore reduced so far as movement by rail is concerned. An example of this is the British Conqueror heavy tank of the 1960s, which had an overall width of 3.96m.

Because of the broader gauge of Soviet railways, the maximum width for unrestricted train movement allowed by them has been 3.32m, instead of 3.15m of the Berne gauge, and Soviet tanks, including the T-54 and T-62 as well as the IS-3, were designed within it. The T-72 has exceeded it but its overall width of 3.72m is reducible to 3.46m and presumably it can be transported by rail on the same basis as other tanks with a width of 3.5m are transported in Western Europe.

Movement by sea has not imposed any general dimensional or weight restrictions on the design of tanks. Obviously, the heavier they are the fewer is the number of ships with decks strong enough or with holds large enough to carry them. The heavier they are the fewer also is the number of ports with cranes capable of lifting them. In consequence, the heavier they are the less mobile they are so far as strategic movement by sea is concerned.

What is more, vessels designed especially for carrying tanks, such as tank landing craft (LCT), and tank landing ships (LST), may not be able to accommodate tanks heavier or larger than those for which they have been designed. However, those of recent origin have been built for tanks as heavy and large as any in general use. Their capabilities should not, therefore, restrict the mobility of tanks when it comes to sea crossings and they are able to deliver tanks on to beaches, which eliminates the problem of port facilities.

For unrestricted road movement in Western Europe, including Britain, the width of vehicles should not exceed 2.5m. This requirement can not be met by battle tanks but light tanks can be designed without their width exceeding this figure and so can other vehicles, such as armoured carriers. However, once they are accepted as special loads, the width of battle tanks ceases to be an issue when it comes to transportation by road. But their weight can be a problem. In particular, if it exceeds 50 tons the total weight of a transporter carrying a tank is likely to be more than 80 tons and this exceeds the capacity of many road bridges. When this happens the number of routes along which tanks can be transported become severely limited and so, consequently, is their strategic mobility.

Movement by air is, in effect, restricted to light tanks, in spite of the existence of transport aircraft capable of carrying battle tanks. This capability was demonstrated vividly in 1976 when a Leopard 2 AV, a battle tank weighing more than 50 tons, was flown all the way from Germany to the United States in a US Air Force C-5A Galaxy. But, although they can carry battle tanks, such aircraft are not likely to be available in sufficient quantity for the strategic movement of a significant number of battle tanks.

Light tanks have a much greater chance of being moved by air because aircraft capable of transporting them are more numerous. The most numerous of them outside the Soviet Union has been the Lockheed C-130 Hercules, which can carry a vehicle of 16 to 17.5 tons and still cover between 3500 and 4300km, the actual range depending not only on the vehicle weight but also on the cruising speed, which is inversely related to the range.

The size of the vehicles which any aircraft can carry is governed by the dimensions of its cargo compartment, the critical dimension being width, which in the case of the C-130 is 2.97m. However, a vehicle carried in it can not be as wide as this because there has to be some dead space around it and this reduces the maximum permissible vehicle width to 2.82m. The maximum width is further reduced if the vehicle is to be delivered using the Low Altitude Parachute Extraction System (LAPES). The military usefulness of LAPES is still to be demonstrated but if it were to be used vehicle width could not exceed 2.72m.

The weight and dimensional restrictions associated with air transport are clearly reflected in the characteristics of three light tanks designed in the United States during the early 1980s, namely the Cadillac Gage Stingray, the FMC Close Combat Vehicle-Light and the Teledyne Armoured Gun System. All three were designed to be transportable in C-130 aircraft and consequently have overall widths of 2.69 to 2.71m and empty weights of between 16 and 17.5 tons.

10.2 Operational Mobility

The second kind of mobility is operational mobility, which implies the ability of tank units to move in the zone of operations. This is a matter of tanks moving under their own power, mainly along roads and tracks but often also cross-country. The speed with which they can do this depends primarily on their power-to-weight ratio. Thus, the higher the power-to-weight ratio of tanks the higher is the average speed with which tank units can move from one area to another.

However, cross-country movement can also be affected by the weight of tanks, which has an adverse effect on it because the ground pressure of heavy vehicles is inherently higher than that of light vehicles. Weight also has an adverse effect on the operational mobility of tanks by restricting the number of road bridges that they can cross and the type of bridging or ferrying equipment which they can use when it comes to the crossing of rivers.

The speed with which tank units can cover long distances and their general freedom of movement also depend on the amount of logistics support they require. In particular, both can be reduced if tanks need to be refuelled frequently. The frequency of the refuelling stops can be minimised, of course, by increasing the amount of fuel which tanks carry but even when this is done refuelling remains a problem because of the quantities of fuel that are required by tank units and the difficulty of ensuring its supply under war-time conditions. The amount of fuel which needs to be supplied increases, roughly, in proportion to the weight of tanks and it increases further if they are not powered by diesel engines but by gas turbines, which consume significantly more fuel. The fuel consumption of tanks also increases considerably when, instead of moving along roads and tracks, they have to move off the roads.

The reliability of tanks also has an important bearing on their operational mobility because the higher it is the greater is the probability that they will arrive where and when they are wanted. Conversely, the more maintenance they require the less likely they are to do so. Reliability is primarily a function of the complexity of tank design but to some extent it is also dependent on the weight of tanks, so that the simpler and the lighter they are the more likely they are to be reliable. Reliability is generally measured in terms of mean time between failures (MTBF), or mean miles between failure (MMBF), while the amount of maintenance that is required is measured in terms of the mean time to repair (MTTR), or the ratio of the maintenance man-hours to operating hours.

10.3 Battlefield Mobility

The third kind of mobility is battlefield mobility, which implies the ability of tanks to move when in actual or imminent contact with enemy forces. This involves movement over various types of terrain, ranging from soft soils to hard rough ground, and negotiating natural and man-made obstacles, such as streams, ditches and trenches, all at the highest possible speed in order to minimise the exposure of tanks to the enemy forces and to provide the opportunity to outmanoeuvre the latter.

The ability of tanks to move over soft soils depends primarily on the pressure they exert on the ground and increases as the pressure decreases. The pressure increases with the weight of tanks, because the size of their tracks and, therefore, of the ground contact area can not be increased in proportion to their weight. In consequence, the ability to move over soft soils generally decreases as tanks get heavier.

On the other hand, the ability of tanks to move at speed over rough ground is governed by their suspensions and in particular by the vertical travel which these provide for the road wheels. Otherwise it is enhanced by the length of tanks and to the extent that their dimensions generally increase with weight the latter may be regarded as beneficial from the point of view of speed over rough ground. For the same reason weight can be, indirectly, an advantage so far as ditch and trench crossing is concerned.

Given a sufficiently low ground pressure and an adequate suspension, the speed with which tanks can move off the roads, as well as on them, becomes a function of their power-to-weight ratio. The same applies to their acceleration, which contributes to the average speed of tanks when they move continuously and which governs how rapidly they can dash over short distances. The latter determines the time for which tanks expose themselves to the enemy while they move from cover to cover and, therefore, their probability of being hit under such circumstances. When it comes to movement over longer distances in terrain which at intervals hides tanks from view, the exposure time and the probability of being hit are governed by the length of the intervisibility segments and the average speed of tanks. But, in either case, exposure time depends ultimately on the power-to-weight ratio, which should be as high as possible therefore if the exposure time and the probability of tanks being hit are to be minimised. However, the benefits of power-to-weight ratio do not increase uniformly with it and it is not, therefore, effective to increase it beyond a certain level, generally considered to be of the order of 25 to 30hp per ton.

Whatever is done to minimise their exposure to enemy fire, tanks can not avoid it and so their battlefield mobility is a function not only of their automotive characteristics but also of their armour protection, which enables them to move freely in the face of possible or actual fire from many enemy weapons. This distinguishes tanks from unarmoured weapon carriers which may be highly mobile in the automotive sense and which may have a high degree of operational mobility but whose battlefield mobility is, nevertheless, inferior to that of tanks because they are highly vulnerable to the fire of machine guns and other light weapons present in large numbers on the battlefield, as well as being vulnerable to artillery shell fragments. In consequence, they can not move as freely as tanks can.

The number of enemy weapons to which tanks are immune depends on the amount of armour they have and this is generally reflected in their weight. As a result, the battlefield mobility of tanks is related to their weight, because the

heavier they are the better is their protection and the greater, therefore, is their immunity to enemy weapons and the freedom with which they can move in face of an enemy. This is in complete contrast to the operational, as well as the strategic, mobility of tanks, which are adversely affected by weight, and makes it important to distinguish between them and battlefield mobility.

There is also a difference between the operational and the battlefield mobility of tanks when it comes to their endurance. In the case of the operational mobility this is a matter of range, that is of the maximum distance which a tank can cover before it needs to be refuelled. The range is generally quoted for steady movement on roads. Off the roads the range is considerably less but conditions affecting it can vary a great deal and are difficult to define. But if the conditions are not defined, as is generally the case, the figures quoted for cross-country range have little meaning.

In the case of battlefield mobility endurance is a question of how long tanks can operate, rather than of the distance they can cover, before they need to be refuelled. It is, therefore, measured in terms of hours covering a mixture of operating conditions representative of a battlefield day. The number of hours of operation aimed at in recent years has been at least 16 to 18, with 20 to 50 per cent of the time being attributed to road movement, 20 to 40 per cent to cross-country movement and the remaining 30 to 40 per cent to standing still with the engine idling. ROLZAS 1/3 + 1/3 + 1/3

10.4 Power, Speed and Rolling Resistance

Apart from weight and power-to-weight ratio, the most frequently quoted measure of the mobility of tanks is their maximum road speed. This can be determined unambiguously by road tests and the maximum attainable speed can be calculated simply and fairly accurately by equating the maximum available engine power to the rate of doing work in overcoming the resistance to motion.

The power available for propelling tanks is not however that normally quoted, which is the maximum gross engine power. It is considerably lower than the latter, first of all because of the power absorbed by the fans required to circulate air for cooling the engine and the transmission. With the commonly used diesel engines this amounts to between 8 and 17 per cent of the gross engine power (10.1). Some power is also absorbed by the electrical generator and any ancillary equipment that may be fitted. Thus, net engine power is generally taken to be not more than 85 per cent of the gross engine power.

More power is lost in the transmission. As a percentage of the power throughput, the amount lost in a typical, well-designed automatic transmission in top gear and at full load is of the order of 10 per cent. But in lower gears and at part load, when internal losses represent a greater proportion of the power flow, it is significantly more. The efficiency of such a transmission is therefore no more than about 90 per cent, at best. Additional power losses occur in the final drives, the efficiency of which is typically about 97 per cent. As a result, the power available at the sprockets to drive a tank amounts to only 70, or at most 74, per cent of the gross engine power (10.2). However, even at full load, it can be only 61 per cent of the gross power (10.3). SEA 2/3

Whatever its value, the sprocket power is related to the maximum possible speed by the following equation:

$$W_S = (F_R + F_D)\ V \qquad \text{10.1}$$

where W_s = sprocket power, W
F_R = rolling resistance, N
F_D = aerodynamic drag, N
V = velocity of tank, m/s

The aerodynamic drag can be calculated using equation 4.9 but, although the frontal area of battle tanks is of the order of 6 to 8m^2 and their drag coefficient is about 1.0, its contribution to the resistance to the motion of tanks is small and in general may be neglected. This leaves rolling resistance as the only force to be considered. It is a force derived from the power absorbed while the vehicle is moving by its running gear, due to friction and hysteresis losses in the tyres of the road wheels, in the rubber bushes of the track pins and so on.

Rolling resistance is generally expressed as a product of the weight of a vehicle and its rolling resistance coefficient C_R, which is commonly described by an equation of the following form:

$$C_R = A + B\ V \qquad \text{10.2}$$

where A and B are constants whose value depends mainly on the type of track with which the tank in question is fitted and V is velocity, as before. However, rolling resistance also depends on track tension, increasing with it, and on the diameter of the road wheels to which it is inversely related (10.4).

The linear relationship between the rolling resistance coefficient and vehicle velocity implied by equation 10.2 is only a rough approximation to the relationship between them and the values of the coefficient vary considerably, as can be deduced from Fig.10.1. The waviness of the curves shown in the figure is due to the resonant vibrations of the running gear, which further complicate the problem of rolling resistance.

Nevertheless, the description of the rolling resistance coefficient provided by equation 10.2 is adequate for many purposes and in the common case of tanks fitted with tracks having double, rubber-bushed pins and rubber pads and running on hard, smooth road surfaces the constant A, which is in effect the rolling resistance coefficient at low speeds, may be taken as 0.030 and B as 0.0009. With all-steel, single-pin tracks the constant A is typically 0.025 and with tracks having sealed, lubricated pin joints with needle bearings A has been as low as 0.015 (10.5).

The maximum possible road speed determined by equating the sprocket power to the rate of doing work against rolling resistance is higher than the actual maximum speed if the peak of the power in top gear does not coincide with the rolling resistance at maximum speed or, graphically, if the power-speed curve does not cross the rolling resistance curve at its peak. Whether it does or not depends on the choice of the ratio for the top gear.

In principle, the same approach can be adopted to calculating the maximum speed off the roads. But in this case there is considerable additional resistance to motion due to the energy absorbed in deforming the soil. This is much more difficult to define than rolling resistance because it varies with the strength of the soil and the pressure exerted on it and because of the difficulty of characterising the soil on which a tank might operate.

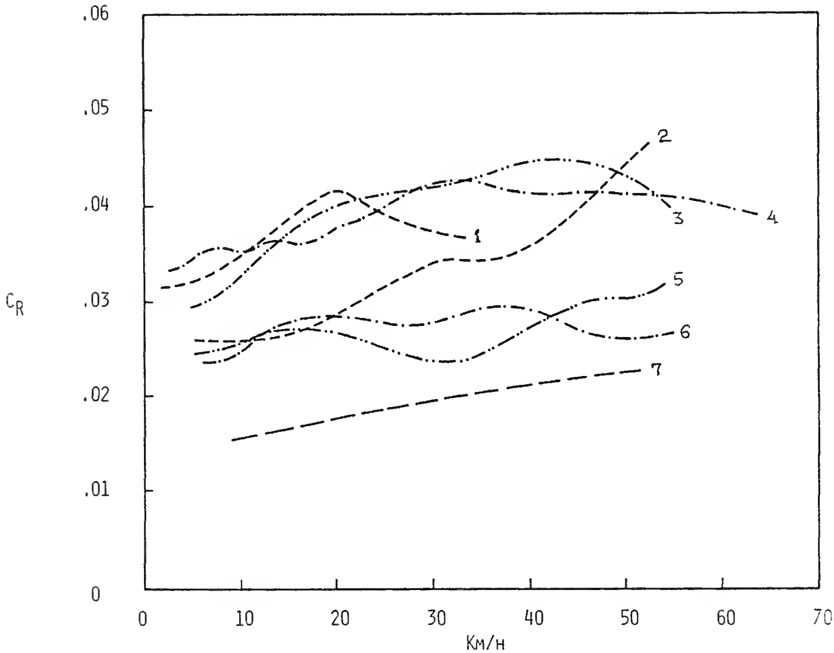


Fig. 10.1 Coefficient of rolling resistance C_R versus speed for vehicles with different types of tracks:
1 = US T23 medium tank
2 = German Leopard 2 tank
3 = US M41 light tank
4 = US LVTP-7 amphibious carrier
5 = British Cromwell tank
6 = US T236 self-propelled gun
7 = German 3/4-track carrier with needle bearing pin joints

In order to simplify the problem the resistance to motion due to the deformation of the soil is often lumped together with rolling resistance. When this is done it is evident that the total resistance to motion is at least 50 per cent greater than the rolling resistance, even on dry grassland. On wet sandy soils the total resistance rises to more than twice the rolling resistance and on soft clay soils, when the sinkage of the tracks becomes considerable, it increases further, to four or more times the rolling resistance (10.6). SEE GENERAL CROSS COUNTRY ▸ 2

10.5 Acceleration and Agility

In contrast to maximum speed, which has been quoted as a mobility characteristic of tanks from the very beginning, acceleration did not begin to gain attention as such until the 1960s. The attention it has gained has been due to a large extent to the interest in the agility of tanks as the basis of evasive manoeuvres that would reduce their chances of being hit and, therefore, increase their battlefield surviva-

bility. The agility of tanks is, of course, very largely a matter of acceleration and the latter has become the principal measure of it as well as being a part of a more comprehensive characterisation of the automotive performance of tanks.

By comparison with velocity, acceleration is more difficult to calculate. It depends, obviously, on the force that is available to propel a vehicle and on its inertia. So far as the propelling force is concerned, what is involved in the first instance is the force that can be generated at the interface between the tank and the ground. The most it can be is the product of the weight of the tank and of the coefficient of traction, which depends on the nature of the ground and to some extent also on the type of track the tank has. In the case of tanks with rubber padded tracks on dry concrete road surfaces the coefficient of traction is generally taken to be 0.7 and this is also its maximum value in most other cases, although 0.8 has been recorded in some instances (10.7). In consequence, for optimum performance, the overall speed reduction ratio in bottom gear of a tank transmission should be such that the net tractive effort provided by the engine, that is the net sprocket torque divided by the sprocket radius, is equal to, or slightly greater than, 0.7 times the weight of the tank. If the net tractive effort were significantly greater than this adhesion between the track and the road surface would be lost and the track would slip, causing wear of its rubber pads with no increase in the force propelling the tank.

On other than hard road surfaces the coefficient of traction can be considerably less than 0.7. For instance, on icy surfaces it can be as low as 0.2, or even 0.1 if the ice is wet. Off the roads it depends on the shear strength of the soils.

If the net tractive effort in bottom gear is equal to 0.7 times the weight of the tank this also satisfies the common requirement that tanks should be able to climb a gradient of 30 degrees, or 60 per cent. In fact, it implies that, in theory, tanks should be able to climb gradients of up to 35 degrees, which is clearly the most that can be expected.

The overall ratio in top gear is governed by the maximum speed of which a tank is capable or any lower speed that may be specified. In theory the overall ratio should vary with speed in such a way that the product of the tractive effort and vehicle speed is constant, which implies that the tractive effort-speed curve should be a rectangular hyperbola. This can not be achieved in practice with geared transmissions but it can be approximated to adequately with a mechanical transmission if it has six or seven gears or with a transmission incorporating a hydrokinetc torque converter and four gears.

So far as the inertia of a tank is concerned, this involves not only its mass to which a translational acceleration is to be imparted but also the inertia of its various rotating parts which must be given a corresponding angular acceleration (10.8). The torque absorbed in this increases with the overall speed ratio and can be considerable, the effect of this on the translational acceleration being to increase the apparent mass of the tank. In consequence, the equation for the acceleration of a tank takes the following form, if aerodynamic drag is ignored, as before, and the tank is on a hard, level road surface:

$$F_T - F_R = m_T (1 + \gamma) \ddot{x} \qquad \text{10.3}$$

where F_T = net tractive effort, newtons
F_R = rolling resistance, newtons
m_T = total mass of tank, kg
$\ddot{x}$ = acceleration of tank, m/s²
γ = inertia mass factor, dimensionless

The factor γ accounts for the inertia of the rotating parts and its maximum value, which occurs in bottom gear, ranges from about 2 to 4 for typical tanks with diesel engines, torque converter transmissions and rubber-bushed and padded tracks. In higher gears, when the overall gear ratios are lower, the values of γ are also lower. SEP 3

Since γ as well as F_T vary with vehicle speed in a manner which can not be expressed analytically, acceleration has to be calculated from equation 10.3 step by step. But even without doing this it should be evident that acceleration increases with power-to-weight ratio, in spite of the fact that the maximum possible tractive effort is limited in all cases to the same value by the coefficient of traction. Thus, the higher the power-to-weight ratio the lower is the required overall gear ratio, which has the threefold effect of reducing the number of gears that are necessary, of increasing the average value of the tractive effort over the speed range and of reducing the value of the inertia mass factor, which clearly increases the acceleration.

The actual acceleration of two typical tanks with different power-to-weight ratios is shown in Fig. 10.2 in terms of curves of velocity and distance covered against time. The tank with the higher power-to-weight ratio can obviously attain a given velocity, or reach a particular distance, more quickly than the other.

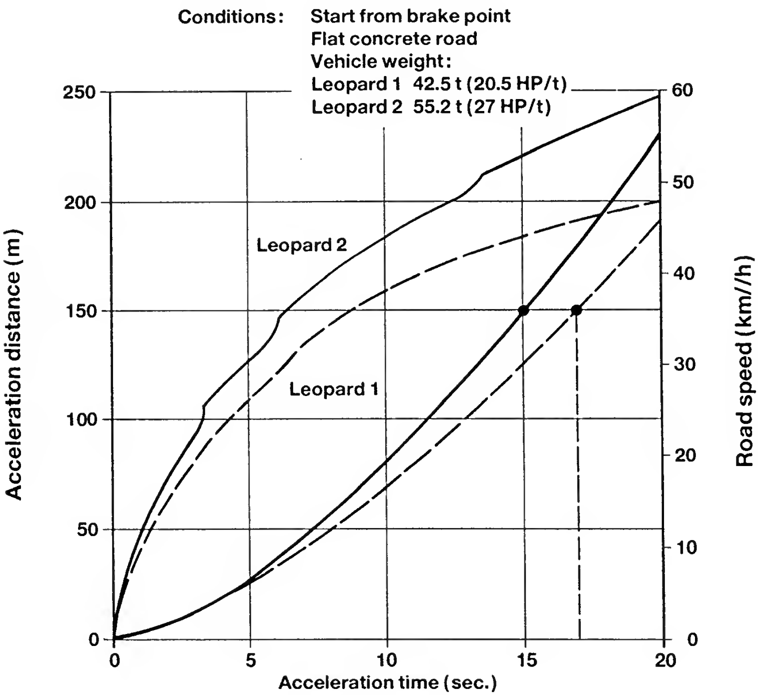


Fig. 10.2 Speed (top) and distance (bottom) versus time of two tanks with different power-to-weight ratios: Leopard 1 (broken curves) and Leopard 2 (solid curves). (MTU)

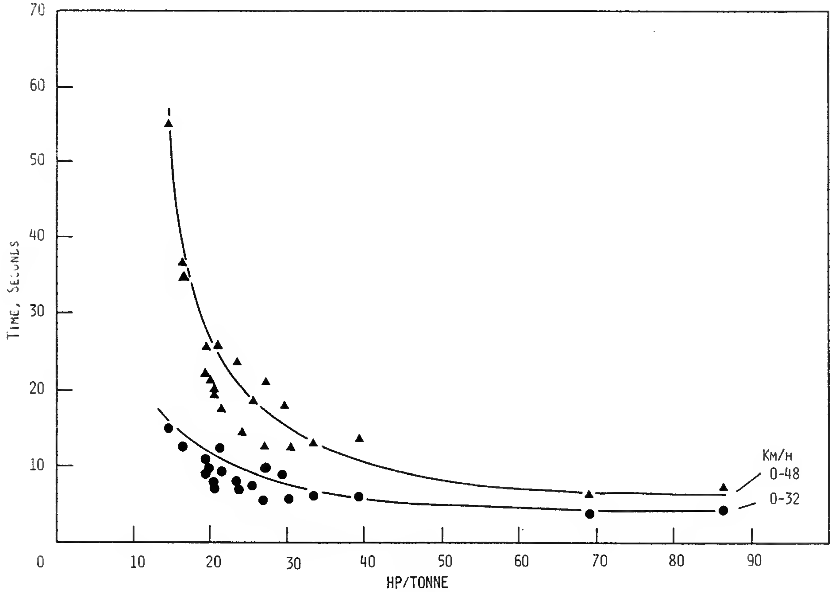


Fig. 10.3 Curves indicating the general trend in the time to accelerate to 32 and 48 km/h versus horse power per ton.

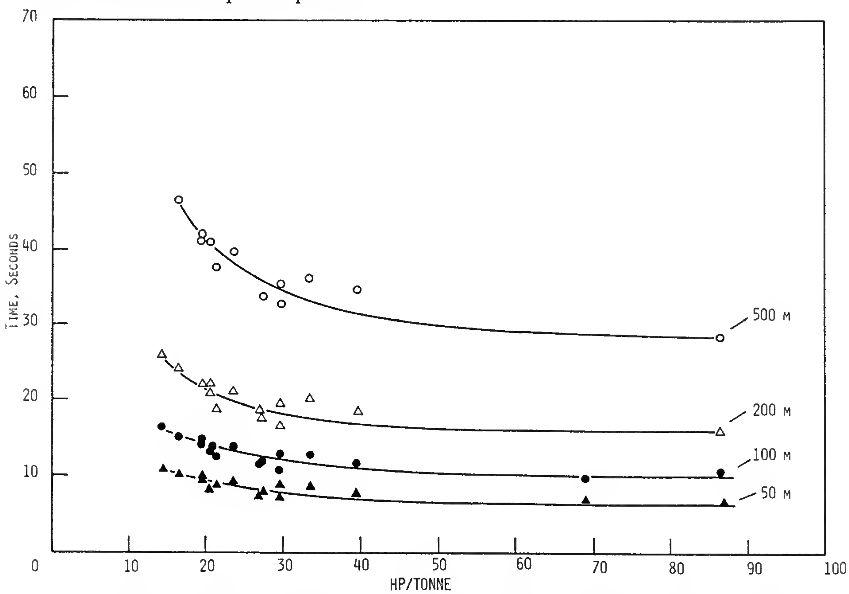


Fig. 10.4 Time taken by vehicles with different power-to-weight ratios to reach successive distances from rest.

The more general effect of increasing the power-to-weight ratio is illustrated in Fig. 10.3 and Fig. 10.4. The first shows the time taken by a number of tanks with different power-to-weight ratios to accelerate on hard road surfaces to 32 and 48 km/hr. The time to accelerate to the higher velocity decreases rapidly at first with increasing power-to-weight ratio but ceases virtually to decrease further once the ratio reaches about 50hp per ton. The time to accelerate to the lower velocity, which is likely to be more common in practice, decreases less rapidly with the power-to-weight ratio and ceases to decrease further at about 40hp per ton.

Increases in the power-to-weight ratio are evidently of value only up to a point, which varies with the circumstances. This is illustrated even more clearly in Fig. 10.4, which shows the time taken by tanks to cover different distances along roads from a standing start plotted against power-to-weight ratio. The curves of Fig. 10.4 indicate the ability of tanks to dash from one position to another and they illustrate that the power-to-weight ratio makes a significant difference to the time only when the distances are relatively long and then only up to about 40hp per ton. Conversely, when the distance is only 50 metres power-to-weight ratio has no significant effect on the time taken to cover it.

10.6 Crossing of Water Obstacles

A special aspect of the mobility of tanks is their ability to cross water obstacles independently of bridges or ferrying equipment. This is particularly important as part of their battlefield mobility but it is also part of their operational mobility.

Water obstacles vary in their nature and so do the problems which they present. The least difficult of them to cross are streams and shallow rivers with low banks, which tanks can ford without preparation provided that the maximum depth of the water is slightly less than the height of the tops of their hulls. This means that

Fig. 10.5 French AMX-30 tank fitted with a schnorkel tube for submerged fording. (French Army)

tanks can ford water obstacles without preparation whenever the depth of the water does not exceed 1 to 1.4 metres.

With some preparation the depth of the water through which tanks can pass can be increased to equal the height to the tops of their turret roofs, that is to between 2 and 2.4 metres, depending on the size of the tank. The amount of preparation which is necessary has been greatly reduced by incorporating in the design of tanks inflatable seals to prevent the entry of water through the turret ring and the gun mounting. Other measures adopted to assist deep fording include provision for operating the engine when its compartment is flooded, which has been done in US tanks from the M47 to the M60 (10.9). Alternatively, the engine compartment has been kept sealed and only the cooling system has been flooded, after disengaging the cooling fans, which has been done in the German Leopard 1.

The value of the deep fording capability of tanks is often restricted, however, by steep banks of rivers and canals, which can not be negotiated by tanks without considerable bulldozing of the banks and the preparation of entry and exit ramps, even though the water in them is not too deep for tanks to wade through. On the other hand, the deep fording capability of tanks makes it possible for them to wade ashore from landing craft even when these can not come right up to the beaches.

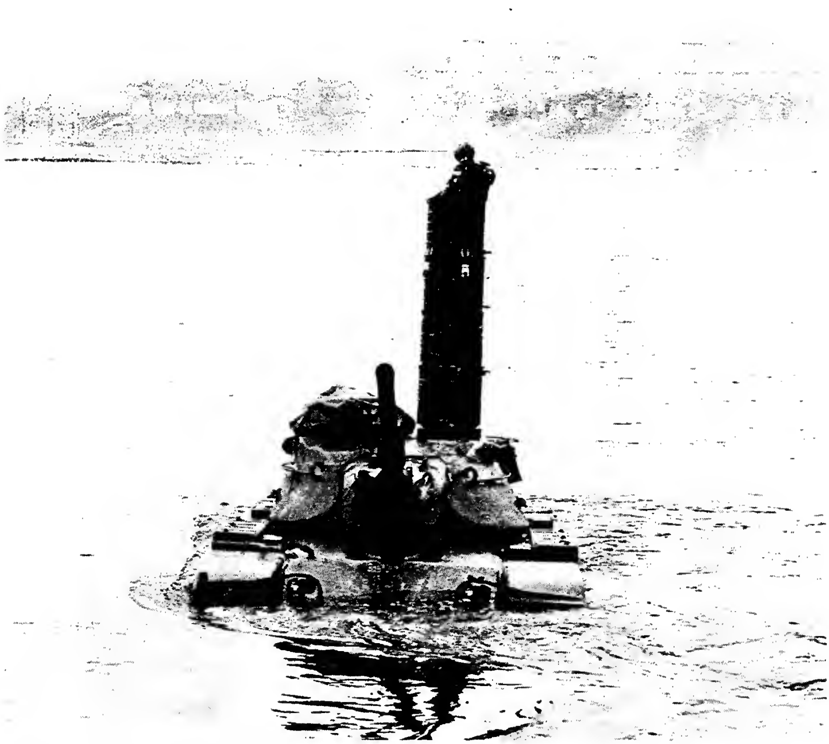


Fig. 10.6 US M60A1 with a large diameter breathing tube emerging after an underwater crossing of the Rhine. (US Army).

Given suitable entry and, even more, exit points, tanks can negotiate even deeper water obstacles by submerged or underwater fording. This began to be explored in Britain in 1939 and in May 1940 a modified A.9 cruiser tank made a successful underwater crossing of the River Stour (10.10). No further progress was made in Britain but in 1940 the idea of wading underwater was taken up in Germany. As a result, a number of Pz.Kpfw.III were modified to wade ashore under water as part of the planned invasion of Britain and they were actually used by the 18th Panzer Division at the crossing of the River Bug on the first day of the German invasion of the Soviet Union in June 1941 (10.11).

Provision for submerged operation was then permanently incorporated in the design of the German Tiger I heavy tank of 1942 but it was not adopted on any scale until the Soviet T-54 was produced after the Second World War. Since then it has been incorporated in all Soviet tanks and during the 1950s it was also embodied in the design of the German Leopard 1 and French AMX-30. Underwater fording kits were also developed during the 1960s for the US M60A1 and the British Chieftain, but neither the US nor the British Army made much use of them and the British Army decided subsequently not to use underwater fording.

Apart from having to be sealed against the entry of water, tanks which are to operate submerged must have a breather, or schnorkel, tube to provide air for the crew and the engine. The schnorkel tube must obviously rise above the surface of the water and its height determines therefore the maximum depth of the water in which tanks can operate; this is generally 4 to 4.5 metres. In all cases the schnorkel tube has been fitted to the top of the turret but there have been two different sizes of it. Thus, in the case of the Soviet tanks and the AMX-30 the tube has been of relatively small diameter whereas German, US and British tanks have had tubes of a diameter large enough for them to act as conning towers in which the commander can stand and observe over its top and which also provide a dry escape route for the crew in an emergency. Apart from its safety aspects, the large diameter tube offers the advantage of the commander standing in it being able to guide the driver. In contrast, tanks with the small diameter schnorkel tubes are blind when submerged and have to be guided from outside by radio.

Another problem facing tanks operating under water is that of developing sufficient traction while they experience a lift equal, according to Archimedes' principle, to the weight of the water which they displace. This problem can be alleviated in part by flooding the engine compartment but tanks may then have difficulty in climbing out of the water, because of the extra weight, until the engine compartment has been pumped dry.

When the water is too deep even for submerged fording the only way that tanks can cross it by themselves is by swimming across it. To be able to do this they generally require additional buoyancy, because their density is too high for them to float unaided. Attempts to provide this additional buoyancy were made from the earliest days of tanks and in most cases took the form of attaching floats of one kind or another to them. But as the weight of tanks grew the size of the floats that were required became impracticable.

A more practical method of providing additional buoyancy has been the use of collapsible flotation screens. This method was devised in 1941 in Britain by N Straussler and flotation screens were subsequently fitted not only to some British tanks but also to a number of US built M4 medium tanks and these were used, with limited success, during the Anglo-American landings in Normandy in June 1944. Since then collapsible flotation screens have been fitted to a number of light armoured vehicles. But they have been adopted on only one battle tank,

namely the Swedish S-tank, which at 39.7 tons has been the heaviest tank to use them. The collapsible flotation screen has the advantage that it can be carried permanently on the vehicle but it is vulnerable to damage and its height, when erected, makes the tank very conspicuous prior to the water crossing.

As the size of the flotation screens grew with the weight of tanks it became increasingly difficult to support them adequately when erected. To overcome this problem a variant was produced in Britain during the 1950s for use with the heavier tanks. It was based on the use of a number of light-weight reinforced plastics sandwich panels erected on a sealed decking at track guard level, which were supported by spring loaded bolsters and straining ropes and which were sealed by a water-proofed fabric cover rolled up over them like a corset. This type of rigid-panel flotation equipment was tried on Centurion and Leopard 1 tanks and it enabled tanks to float in relatively rough off-shore waters, which made it suitable for use in landing operations. However, it constituted a relatively clumsy and slow method of crossing rivers and other water obstacles and its use has not been pursued further.

Only relatively light armoured vehicles can have sufficient buoyancy to float without aids and even then they need to be large in relation to their weight. A good example of this has been provided by the Soviet PT-76 amphibious reconnaissance tank, which is as large as a battle tank and yet only weighs 14 tons.

Once they are able to float, tracked vehicles can propel themselves in water by means of their tracks. This removes the necessity of fitting them with additional means of propulsion but, unfortunately, tracks are very inefficient as a means of propulsion in water. In fact, on the basis of the conversion of the net sprocket power into propulsive power, the maximum efficiency is only about 10 per cent (10.12). The reasons for the low propulsion efficiency, which may be only 5 per cent, or even less, include the poor hydrodynamic performance characteristics of the tracks and the power absorbed by them when vehicles float, because they are then highly tensioned by the suspension relieved of the vehicle's weight. The propulsive efficiency can be improved somewhat by shrouding the top run of the tracks and with special tracks it may reach 15 per cent, but such tracks are not suitable for general use on land.

In view of all this and the high resistance to motion in water of bluff bodies like the hulls of armoured vehicles, the speed of vehicles propelled in water by their tracks is low, the maximum ranging from about 5 to 8 km/hr. In consequence, they may be unable to negotiate fast flowing rivers. Thus, if armoured vehicles are to swim across such rivers they must be fitted with propellers or with water jet propulsion units.

Propellers have been fitted to a number of amphibious light tanks as well as other armoured vehicles but, because of the adverse flow conditions around the rear of the hulls where they have to be fitted, they can not operate with a propulsive efficiency of more than about 20 per cent and they are also vulnerable to damage. In contrast, water jet propulsion units can be incorporated in the structure of vehicles in such a way that they are not exposed to damage, although they then take up a considerable amount of space. However, they can have a propulsive efficiency of up to 30 per cent (10.13). As a result, vehicles fitted with them, like the Soviet PT-76, have had a maximum speed in water of 10 km/hr and in some cases even 13.5 km/hr (10.14).

Apart from the higher maximum speed, the provision of separate means of propulsion in water helps to overcome the difficulties which vehicles propelled only by their tracks encounter when they are about to come out of the water. At

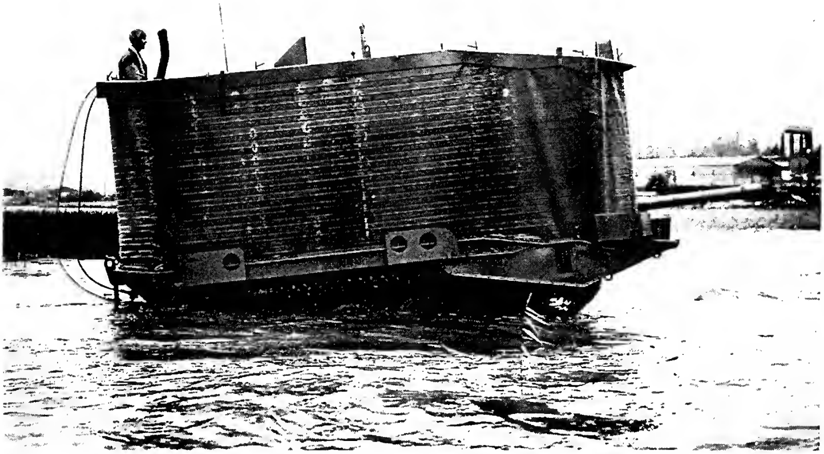


Fig. 10.7 Swedish S-tank with its flotation screen erected for swimming. (Swedish Army).

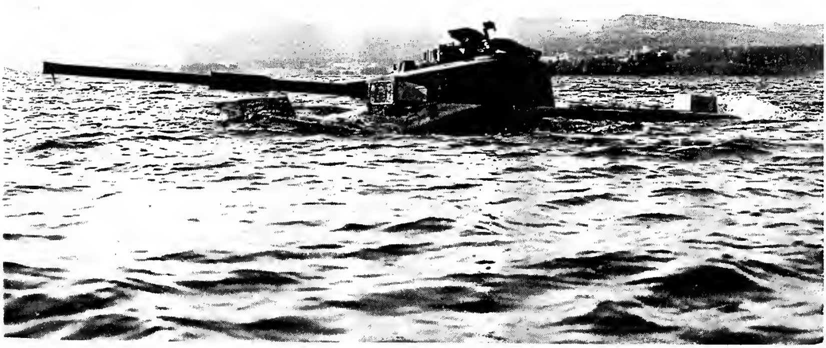


Fig. 10.8 Swedish Ikv 91 tank destroyer which, like the Soviet PT-76 reconnaissance tank, can swim without preparation. (Hägglund & Söner)

that point they lose whatever thrust the tracks developed in water but they are still partly supported by their buoyancy, which reduces the weight acting on the tracks and, therefore, the traction they can develop. In consequence they are difficult to control and may not develop sufficient traction to begin to climb up the bank. By comparison, vehicles with separate means of propulsion are far better able to come out of the water because they can thrust themselves at the banks at greater speed and under greater steering control and, as they do this, have their tracks running at low speed, in the low gear appropriate for climbing up the bank, instead of having them running at high speed.

Vehicles with separate means of propulsion and in particular with twin water jet propulsion units are also much more manoeuvrable in water. The ability of vehicles to enter water and their trim can also be improved by giving them a raised bow, or prow. But this tends to reduce the driver's vision on land and in general the better they are at crossing water obstacles the less efficient they are as ground vehicles. Thus, vehicles like the PT-76 have little to commend them, except that they are good at swimming without preparation across rivers and lakes.

Amphibious vehicles used for landing operations from the open seas have to be even more specialised because they have to swim in much rougher waters and may even have to negotiate plunging surf 3 metres high (10.15). This requires them, among others, to have a much greater freeboard than vehicles intended to operate only in calm inland waters. Amphibious armoured vehicles of this kind are exemplified by Landing Vehicles, Tracked (LVT), three generations of which have been produced since 1941 for the US Marine Corps (10.16).

10.7 References

10.1 *Military Vehicle Power Plant Cooling*, AMCP 706-361, US Army Materiel Command, Washington, 1975, pp.2-18.

10.2 N R Murphy, 'Armored Combat Vehicle Technology', *Armor*, Vol.91, No.5, November-December 1982, pp.24-25.

10.3 G V Cleare, 'Factors Affecting the Performance of High-Speed Track Layers, *Proceedings of the Institution of Mechanical Engineers*, 1963-64, Vol.178, Pt.2A, No.2, pp.51-52.

10.4 Ibid., pp.52-53.

10.5 W J Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, p.33.

10.6 G V Cleare, op.cit., pp.57-59.

10.7 W Merhof and E M Hackbarth, *Fahrmechanik der Kettenfahrzeuge*, Leuchtturm-Verlag, Alsbach, 1982, p.49.

10.8 J L Koffman, 'Vehicle Performance, the Effect of Rotating Masses on Acceleration', *Automobile Engineer*, Vol.45, No.12, December 1955, p.576.

10.9 R P Hunnicutt, *Patton*, Presidio Press, Novato, 1984, pp.311-316.

10.10 H W Kenyon, *Conversion of Service Tank to Enable it to Proceed Completely Submerged*, Permanent Record of Research and Development, Monograph No.8, 005, Ministry of Supply, London, 1948.

10.11 P Chamberlain and H L Doyle, *Encyclopedia of German Tanks of World War Two*, Arms and Armour Press, London, 1978, pp.70-71.

10.12 G V Cleare, op.cit., p.64.

10.13 D Wray, *New Assault Amphibian Personnel Carrier (LVTPX 12) for the US Marine Corps*, SAE Paper No.680533, Society of Automotive Engineers, New York, 1968, p.8

10.14 Ibid., p.9.

10.15 Idem, p.1.

10.16 *Research, Investigation and Experimentation in the Field of Amphibian Vehicles*, Ingersoll Kalamazoo Division, Borg Warner Corporation, Kalamazoo, 1957.

Chapter 11

Tank Engines

11.1 Spark-Ignition Piston Engines

When tanks began to be developed in 1915 virtually the only type of engine available for the propulsion of vehicles was the internal combustion engine with reciprocating pistons and with electric spark ignition of the volatile hydrocarbon fuel, that is petrol or gasoline, which constituted its source of energy. In consequence it was this type of engine which was used to power the first tanks.

Moreover, the first tanks were powered by existing models of this type of engine which had been developed earlier for other purposes. In particular, the first British tanks were powered by a 6-cylinder liquid cooled engine of 105 hp* which was produced originally by the Daimler Company for a large wheeled tractor. The use of such an engine to power the first tanks set an example which has been followed on numerous subsequent occasions. Thus, many tanks have been powered by engines which had been produced by the automotive industries for other purposes. This has saved the time and money that would have been needed to develop and to build special engines. But the successful use of existing engines has been confined in most cases to relatively light tanks, because the automotive industries have not produced engines that would give heavier tanks a sufficiently high power-to-weight ratio. An early example of this was the use of an existing automotive engine in the British Mark I tank, which gave it a power-to-weight ratio of less than 4hp per ton and this soon led to the realisation that there was a need for more powerful engines (11.1).

In consequence, engines more powerful than those produced by the automotive industries for civilian purposes began to be developed for the heavier tanks. The first of them was already produced in 1918, for the British Mark V tanks. It is interesting to note that its designer, H R Ricardo, still employed cross-heads to guide its six pistons, as in the steam engines from which the spark-ignition piston engine was mechanically derived. The engine was originally rated at 150hp but its cylinders were subsequently bored out and it eventually produced 225 hp (11.2).

However, by 1918 an alternative source of more powerful engines had emerged. It was the aircraft industry which had by then developed relatively light and compact engines of more than 300 hp. One of them was the 338 hp Liberty aero

* Unless otherwise stated, hp is the measure of the maximum gross horse power in Anglo-American units in which the engines concerned have been generally described and equals 746 W; metric hp (PS, CV) = 736 W.

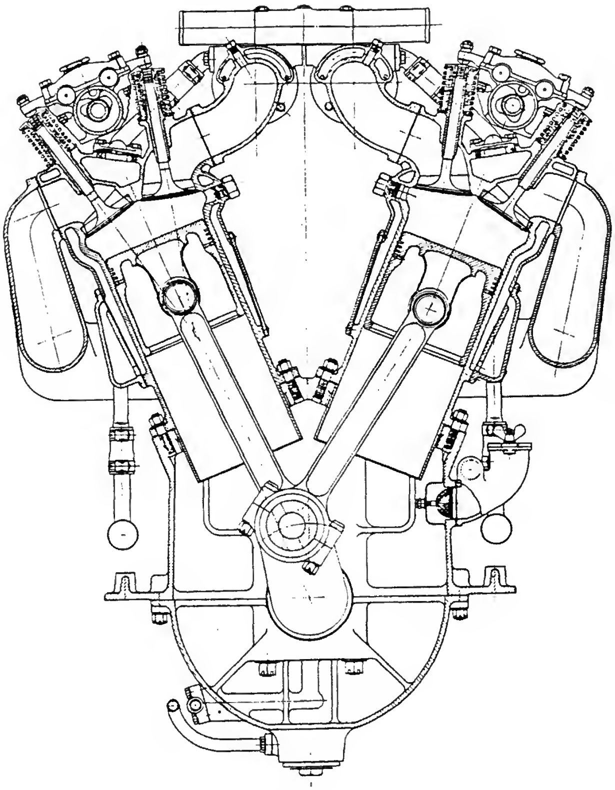


Fig. 11.1 Liberty engine developed during the First World War and produced again during the Second World War for British cruiser tanks.

engine, which had been developed in the United States and which was adopted in 1917 for the Anglo-American Mark VIII heavy tank. The latter was to have been produced on a large scale in 1919 and pioneered the use of aero-engines in tanks, which was to be a major feature of their development until after the Second World War. Moreover, the Liberty engine introduced the liquid cooled V-12 configuration, which has been a common feature of battle tank engines to this day, although they have not followed its example of an exceptionally narrow angle of 45° between the two banks of cylinders.

The Liberty engine itself was used to power J W Christie's experimental, high-speed tanks of 1928 and 1931 (11.3). It was then resurrected in 1936 by the British Army as the only engine that could be produced quickly enough for its new cruiser tanks with the Christie suspension. Thus, it was built in Britain as the Nuffield-Liberty engine and powered the A.13, Crusader, Cavalier and Centaur cruiser tanks of 1939-1944. Its output of 340 hp was virtually the same as that of the original version, built 20 years earlier, although it was eventually made to produce 395 hp. Nevertheless, the Nuffield-Liberty was powerful by the standard of contemporary tank engines. But by the time it came into use a considerably more powerful engine had been produced for tanks in the Soviet Union.

The Soviet engine was the M-17, a large, 46.9 dm^3 V-12 of 500 hp, which powered the BT, T-28 and T-35 tanks (11.4). It was again a ground version of an

aero engine, its design being based on a BMW aircraft engine, a 6-cylinder 250 metric hp version of which powered the Krupp and Rheinmetall *Grosstraktoren* tested in the Soviet Union between 1929 and 1932 (11.5).

The US Army also turned during the 1930s to aero engines. Its first choice was a 7-cylinder radial engine of 250hp, which was produced by the Continental Motors Corporation and which was first tried in 1931 in the T2 Combat Car. This was followed by the adoption of radial aero engines for other light tanks and then also for medium tanks, up to and including the M4A1 of 1942, which was powered by the Wright-Continental R975CA 9-cylinder radial engine of 460hp.

However, even before the United States entered the Second World War, the demand for tank engines outran the availability of the radial engines, which were also required for training aircraft. This forced the US Army to use other types of engines for its tanks. One of them was the Ford GAA, a 18 dm^3 V-8 version of a liquid-cooled V-12 aero engine, which developed 500hp and which was adopted to power the M4A3 medium tank. The Ford GAA was more powerful than any other engine used in the M4 medium tanks and its configuration was also much more appropriate to the installation in tanks than that of the radial engines. In consequence, it became the preferred type of US medium tank engine and powered most of the M4 tanks produced during the latter part of the war, as well as the M26 tanks which followed them.

The British Army also successfully and more directly adopted the Rolls-Royce Merlin aero engine, which powered the Spitfire and Hurricane fighters of the Royal Air Force. In its Meteor tank form this 27 dm^3 liquid-cooled V-12 engine developed 600 hp and was first used in 1943 in the Cromwell cruiser tank, after which it also powered the Comet and then the Centurion tanks.

Contemporary German medium and heavy tanks were powered by Maybach engines which were specially designed for them but which were, nevertheless, more closely related to aero engines than anything else. They were all liquid-cooled V-12 engines but ranged in size from the 10.84 dm^3 HL 108 TR of 250 metric hp, which powered the original versions of the Pz.Kpfw.III, to the 23.1 dm^3 HL 230 of 700 metric hp, which powered the Panther and Tiger II tanks.

The output of the HL 230 engine amounted to 30 metric hp per dm^3, which was higher than that of any other tank engine used up to the end of the Second World War. The HL 230 was also in advance of other engines in having a maximum gross brake mean effective pressure of 10 bar and a maximum mean piston speed of 14.5 m/s, which was as high as that of the contemporary aero engines. Other engines in its class, such as the Ford GAA and the Meteor, had a somewhat lower specific output but they were still superior in this respect to other contemporary engines and to this extent they and the HL 230 represented the best type of engine available at the time for tanks.

The specific output of engines of this type increased still further with the development of fuel injection, which was already widely used during the Second World War in German aircraft engines. In particular, the Maybach HL 234 engine, the fuel injection version of the HL 230 which was developed towards the end of the war, produced 900 instead of 700 metric hp. Similarly, a fuel injection version of the Meteor, which was developed during the 1950s for the Conqueror heavy tank, produced 810 hp instead of 650 hp of the contemporary carburetted version. The Maybach HL 295 engine, which powered the French AMX-50 tanks of the same period, had an even higher output of 1000 metric hp, out of a swept volume of 29.5 dm^3 which meant 34 metric hp per dm^3.

Engines of this kind enjoyed the advantage of a high specific output for several

years after the Second World War and the Meteor continued to be fitted in Centurion tanks until their production ended in 1962. However, by then piston aero engines had been superseded by aircraft gas turbines and they ceased to be available for adaptation to tanks, or to serve as a model for tank engines. As a result, tanks came to be powered by other types of engines, almost all of which were specially designed for them.

11.2 Twin-Engine Power Units

While adaptations of aero engines and other engines of a similar kind were successful in meeting the power demands of tanks not enough of them were available at times to meet the need for engines more powerful than those produced by the automotive industries. In consequence, the latter were used not only to power light tanks but also to power a number of heavier tanks. However, in that case they could only provide enough power if more than one engine was installed.

Two engines were actually used to power a tank as early as 1918, the tank being the British Medium A. But in that case the reason for the use of two engines was to drive the tracks separately and consequently to steer the tank by varying the speed of the engines, which was subsequently recognised as a very inefficient method of steering.

The first tank to enter service with two engines geared together to obtain more power was the British Matilda infantry tank, which was designed in 1937 and which was powered by two 6-cylinder AEC diesels each developing 87 hp. The example of the Matilda was followed in 1941 in the United States where a twin engine power unit was adopted for the M3A3 and M3A5 and then for the M4A2 medium tanks. It consisted of two General Motors 6-71 truck diesels, each of which developed 205hp (11.6). Twin engines were subsequently also used in the M5 and M24 light tanks.

The idea of using more than one engine was carried a stage further in 1941 in Australia where the Sentinel tank which was then being developed was powered by three V-8 Cadillac car engines, as no other engines could be obtained (11.7). The ultimate in this line of development was reached in the United States where in 1941 five 6-cylinder Chrysler car engines were assembled into the A57 multi-bank engine which produced 425hp and which was made to power the M3A4 and M4A4 medium tanks.

The use of a power unit like the Chrysler multi-bank engine could only be justified in an emergency, when there was a dire shortage of other engines, because of its complexity and because it was considerably larger and heavier than a single engine of the same power. To a somewhat lesser extent the same applies to twin-engine power units. Against this, twin-engine power units have enjoyed the economic advantage of being made up of existing truck or other engines. Otherwise the only point in their favour has been that they provide a degree of redundancy as each of the two engines can be operated independently of the other and can drive a tank by itself if the other fails, which reduces the risk of immobilisation.

However, in spite of their disadvantages, twin-engines have been proposed again for tanks since the Second World War and they have been used in a number of other armoured vehicles. The latter include the US M59 tracked armoured carrier introduced in the 1960s and the French Panhard Sagaie 2 armoured car of the mid-1980s. A twin-engine power unit was also adopted for the Swedish S-tank, although in its case there were additional reasons for using two instead of a single engine and they are referred to later.

11.3 Air versus Liquid-Cooled Engines

The engines which powered the earliest tanks were all liquid-cooled but an alternative to them in this respect emerged in 1923 in Britain with the appearance of the Vickers Medium tank powered by a 90hp air-cooled V-8 engine produced by the Armstrong Siddeley company. A much more powerful 370hp V-12 air-cooled engine was built by Armstrong Siddeley in 1926 for the experimental multi-turreted Independent tank and 180hp V-8 air-cooled engines were also built for the A.6 Sixteen-Tonners. In addition, Armstrong Siddeley produced a four-cylinder air-cooled engine of 87hp for Vickers-Armstrongs' Six-Ton Tank.

However, development of the air-cooled Armstrong Siddeley tank engines came to an end around 1932 when, because of a shortage of funds, the British Army decided to power its new tanks by the less expensive adaptation of a liquid-cooled AEC bus engine. No concern appears to have been voiced about the abandonment of air-cooling and, although a few more of the smallest Armstrong Siddeley engine were made until 1939, there has been no further interest in Britain in air-cooled engines for tanks.

There has also been little interest in air-cooled engines in Germany where their use in tanks was confined to the horizontally-opposed four-cylinder Krupp M 305 engine of 60 metric hp which powered the original, Model A version of Pz.Kpfw.I produced between 1934 and 1936. The only other German armoured vehicle to go into service with an air-cooled engine was the second version of the heavy eight-wheeled armoured car of 1943-1945 which was powered by Czech-built Tatra 103 V-12 diesel of 220 metric hp.

There appears to have been equally little interest in air-cooled engines in the Soviet Union, although a copy of the Armstrong Siddeley four-cylinder air-cooled

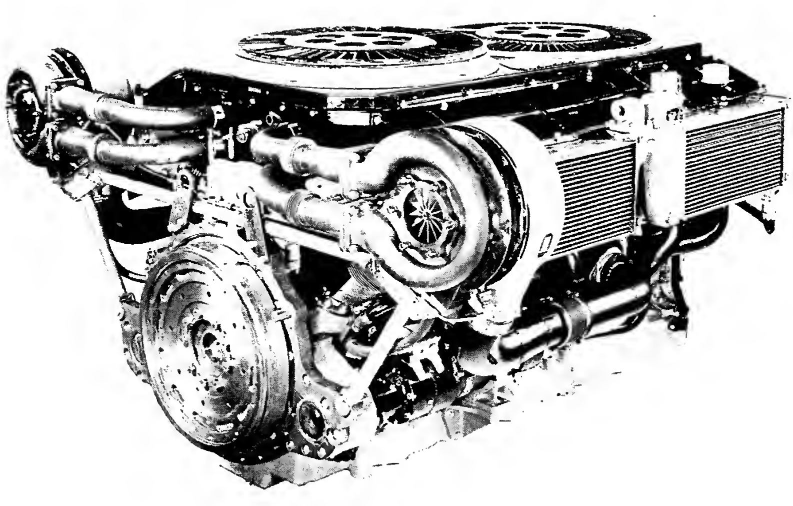


Fig. 11.2 Continental air-cooled AVDS-1790 engine which has powered several US tanks. (Continental Motors)

engine was used on a large scale until 1941 in the Soviet T-26 version of the Vickers-Armstrongs Six-Ton Tank.

On the other hand, air-cooled engines have been used extensively in US and Japanese tanks. The Ordnance Department of the US Army became convinced of the advantages and practicability of using air-cooled engines in tanks after the installation of a 6-cylinder Franklin engine in some of the US copies of the Renault FT between 1929 and 1931 (11.8). However, the US Army was short of funds at the time and could not afford to develop a special air-cooled tank engine. The Ordnance Department therefore decided to use an existing engine that came nearest to its requirements. This led to the adoption of the R-670 aero engine, an air-cooled 7-cylinder radial of 250hp which was being produced by Continental Motors Corporation. As a result the R-670 was used to power US light tanks from the T2 of 1934 to the M3A3 of 1943. It also powered the T4 medium tank of 1935 but heavier medium tanks, from the M2 of the 1939 to the M4A1 of 1942, were powered by another and more powerful air-cooled radial engine, the 9-cylinder Wright R-975, which was originally rated at 346hp and eventually at 460hp.

It was only during the Second World War, when the demand for tank engines exceeded the supply of the air-cooled radial engines, that some US tanks were powered by liquid-cooled engines. However, the US Army Ordnance Department continued to prefer air-cooling for tank engines. In consequence, when it decided in 1943 to develop new engines for tanks it required them to be air-cooled. It also required them to have a V or a horizontally opposed arrangement of the cylinders instead of the radial configuration which was used of necessity until then but which was recognised to be far less suitable for tanks, principally because of its height (11.9).

The new US tank engines were developed by Continental Motors as part of a family of air-cooled engines based on a common cylinder size. The largest and the most important of them was the AV-1790, an air-cooled V-12 with a swept volume of 29.36 dm^3, or 1790 in^3, which accounted for its numerical designation. It developed 810hp and it began to be produced in 1949, originally for the M46 medium tank (11.10). It was then used to power the M47 and M48 medium tanks and, after being converted from a spark-ignition engine into the AVDS-1790 diesel, it was also installed in the M60 series of battle tanks which were produced from 1960 until 1987. In addition, the AVDS-1790 has been retrofitted in four different countries in Centurion tanks, in place of their original liquid-cooled Meteor engines.

Apart from AV-1790 and AVDS-1790, Continental Motors also developed other air-cooled tank engines. In particular, during the mid-1960s Continental Motors developed the AVCR-1100, an air-cooled V-12 diesel with a swept volume of 23.2 dm^3 and an output of 1475hp, which powered the US prototypes of the MBT-70 while the German prototypes of it were powered by the liquid-cooled MB 873 Ka 500 produced by MTU. The AVCR-1100 was developed further during the 1970s into the AVCR-1360 of 1500hp, which powered the General Motors prototype of the US XM-1 tank.

Similarly, the Japanese Army had consistently used air-cooled engines ever since it developed the Type 92 light tank in 1932. What is more, during the 1930s it was the first to produce a family of air-cooled tank diesels based on a common cylinder size (11.11). When the development of tanks was resumed in Japan in the 1950s and led to the production of the Type 61 medium tank this was again powered by an air-cooled engine, the Mitsubishi 12HM21WT diesel of 650hp. The next Type 74 medium tank has also been powered by an air-cooled engine, the Mitsubishi

10ZF22WT two-stroke diesel of 870hp. But the TK-X tank designed to follow the Type 74 is powered by a liquid-cooled diesel of 1500hp.

The principal attraction of the air-cooled engines has been that they dispense with the coolant, radiators and plumbing of liquid-cooled engines which made them vulnerable to damage and unreliable, because of the difficulty of making them leak-proof. The unreliability of liquid cooling systems was brought out by the early aero engines and resulted in air-cooled engines being generally favoured for aircraft during the 1920s, which encouraged their use in tanks. Experience with military aircraft also showed that air-cooled engines were less vulnerable than liquid-cooled engines to battle damage and in particular to being hit by bullets, which favoured their use in ground attack and similar aircraft (11.12).

However, the reliability of liquid cooling systems gradually improved until it ceased to be an issue so far as tanks are concerned and their vulnerability to battle damage became little different from that of air-cooled engines when these came to require large oil coolers. Moreover, the vulnerability of both types of engines to battle damage has been reduced by the development of ballistic grilles for the air intake and exhaust openings of armoured vehicles, which has reduced the risk of bullets and shell fragments entering engine compartments. Radiators of liquid cooling systems have remained vulnerable to clogging by dust and dirt and this has been regarded as another point against them but in general they are not more vulnerable to it than the cylinder cooling fins of air-cooled engines.

Early objections to liquid-cooled engines on the grounds of the danger of the coolant freezing in the winter have been overcome by the addition to the cooling water of ethylene glycol anti-freeze compounds, which can lower the freezing point of the coolant to below -54°C for arctic operation (11.13). At the same time the risk of the loss of coolant has also been reduced by the use of sealed cooling systems and this has been of particular benefit to liquid-cooled engines in desert or arid areas where it might be difficult to replenish them with cooling water.

In theory, air-cooled engines have an advantage in that the cooling fins of their cylinders operate at a higher temperature than radiator surfaces. This implies a greater temperature difference between them and the cooling air and, therefore, less air being required to carry the heat away. However, radiators can transfer heat to the cooling air more effectively than the cylinders of air-cooled engines, even when the latter are well baffled or cowled, and the mass flow of the air required to cool the two types of engines has not been as different as has been claimed sometimes (11.14). In fact, the cooling air mass flow of recently designed diesels of both types has been of the order 60 to 70 kg/kWh, including the air required to cool the oil of their associated transmissions.

Whatever the difference between the amounts of cooling air required by the two systems, air-cooled engines are more difficult to cool thoroughly, because there is no flow of coolant to direct at hot-spots. Air-cooled engines are not therefore considered to be capable of as high a specific output as liquid-cooled engines. Nevertheless, one of the tank diesels with the highest specific output to be produced so far, the Teledyne AVCR-1360, has been air-cooled.

Air-cooled engines are undoubtedly somewhat longer than comparable liquid-cooled engines because their cylinders have to be spaced more widely apart on account of the cooling fins. But when the radiators are added to the liquid-cooled engines and the two types are compared together with their cooling systems there is relatively little difference between their bulk. Precisely how much their volumes differ is difficult to establish for lack of strictly comparable data. The same applies to the total weight of the two types of engines, although on the whole air-cooled

engines appear to be lighter. On the other hand they are generally considered to be more expensive to produce.

11.4 Adoption of Diesel Engines

Soon after being presented with the choice between liquid and air-cooled engines, the designers and users of tanks also began to face the choice between spark-ignition and compression-ignition, or diesel, engines. The first of the tank diesels was designed and built by Ricardo & Co., whose founder had already designed the first engine to be produced specifically for tanks. The engine was developed under contract from the British Army, following some earlier work on diesels for aircraft (11.15). It was a 4-cylinder, liquid-cooled, sleeve-valve engine of 90hp and it was installed for trials in a Vickers Medium tank in 1927. Subsequently six more diesels were built by Ricardo & Co. for tanks, including a 6-cylinder engine of 180hp which was tested in 1933 in one of the Sixteen-Ton medium tanks. But the development of special diesel engines for tanks then came to an end in Britain for lack of money. Instead some British tanks were fitted with adaptations of commercial diesels, the first of them being the A7E3 experimental tank of 1935, which was powered by two AEC bus diesels. Similar engines were later used in pairs in the Matilda and singly in the early Valentine infantry tanks, the later Valentines being

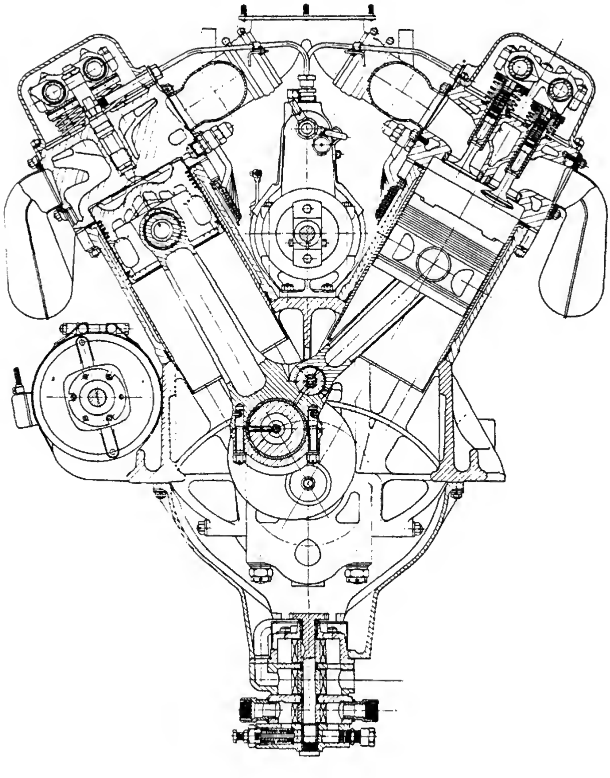


Fig. 11.3 V-2 diesel which has powered the T-34 and other Soviet tanks over a period of 50 years.

powered by General Motors two-stroke diesels. Otherwise British tanks continued to be powered by spark-ignition engines and it was only in the 1950s that a tank diesel was again developed in Britain.

In the meantime, diesels were adopted for tanks in other countries. The first of them was Japan, where the development of a diesel engine for tanks started in 1932. This led to its installation in a Type 89B medium tank in 1934 and the subsequent adoption of diesel engines for all Japanese tanks (11.16).

At about the same time the Polish Army adopted a Swiss-designed Saurer diesel for its derivative of the Vickers-Armstrongs Six-Ton Tank, the 7TP, which first ran in prototype form in 1934. Two years later the French Army adopted a Berliet-Ricardo diesel for the FCM 36 light tank, but only 100 of it were produced, all other French tanks continuing to be powered by spark-ignition engines. In the mid-1930s the Italian Army also decided to use a Spa V-8 diesel in its new M 11/39 medium tank, the trials of which started in 1937, and later also adopted diesel engines for its M 13/40 and M 14/41 medium tanks.

The largest scale use of diesels in tanks came with their adoption by the Soviet Army. This followed the development for tanks of the BD-2 diesel, a liquid-cooled V-12 which originally produced 400 metric hp at 1700 revolutions per minute and which was first tested in a BT-5 tank in 1933. After further development the BD-2 was renamed the V-2 and was adopted in 1939 as the standard medium and heavy tank engine. In consequence it began to be produced in 1940 for the KV-1 heavy tank, in which it was rated at 600 metric hp at 2000 rev/min, and for the T-34, in which it was rated at 500 metric hp at 1800 rev/min. It was also installed in the final models of the BT series of tanks and continued to power all Soviet medium and heavy tanks up to and including the T-72 of the 1980s, by which time it was fitted with a mechanically driven supercharger and produced 780 metric hp at 2000 rev/min.

In contrast, the German Army decided during the 1930s to concentrate on spark-ignition engines for tanks. But this decision was taken mainly because it was considered that gasoline would be more readily available than diesel fuel and not because of the relative merits of spark-ignition and diesel engines. A similar decision in favour of spark-ignition engines was taken during the Second World War in the United States, where the National Petroleum Board decided on the basis of the availability of fuels that military vehicles should use gasoline. Prior to this the US Army had been experimenting with Guiberson air-cooled radial aircraft diesels as a possible alternative to the radial spark-ignition engines and one of them was installed in the T5E2 Combat Car as early as 1936. However, the Guiberson diesels were only used on any scale in some of the M3 light tanks and their further use was rejected in 1942 by the Chief of the Armored Force (11.17). This did not prevent the experimental installation of several other diesels in M4 medium tanks, or the production of 10 968 M4A2 medium tanks with the twin General Motors diesel engines. But 87 per cent of the latter were sent to British, Soviet and other allied forces and the rest were only used by the US Army for training (11.18).

It was only in 1956 that the US Army began to change its fuel policy, allowing jet engine fuel to be used in armoured vehicles, and in 1958 it finally permitted the use of diesel fuel. This led to a switch from spark-ignition to diesel engines, which the Ordnance Department had favoured since the early 1940s (11.19). Moreover, it had already initiated work in 1954 on the conversion of the standard AV-1790 spark-ignition tank engine into a diesel. The outcome of it was the AVDS-1790, a diesel engine of 750hp, which was adopted in 1959 for the M60 battle tank (11.20).

By then the German and French Armies had also decided that the new tanks which they began to develop in the mid-1950s and which became the Leopard 1 and the AMX-30, should be diesel powered. Similarly, the British Army decided in 1958 that its new tank, which became the Chieftain, should have a diesel engine. A year earlier the Swiss Army also adopted a diesel for what was to be its Pz.61 battle tank.

In fact, diesels were universally accepted during the 1950s as the most suitable engines for battle tanks. Subsequently they were also generally adopted for other armoured vehicles. Only the lightest of them continued to be powered by spark-ignition engines, which in their case have been adaptations of car engines. The latter have been used simply because there were no other engines of the relatively low power required by light armoured vehicles or because they were still lighter and simpler than comparable diesel engines, as well as cheaper.

The combination of a relatively high specific output and low cost led to the adoption of a militarised version of the Jaguar car engine for the Scorpion light tank which the British Army developed during the 1960s (11.21). As installed in the Scorpion, the 6-cylinder 4.2 dm^3 Jaguar engine developed 190hp, or 45hp per dm^3, which represented a higher specific output than that attained during the 1950s with the final, fuel-injected versions of the spark-ignition battle tank engines. Nevertheless, the Scorpion appears to have been the last tank to be built with a spark-ignition engine and its final, export version has been fitted with a diesel engine.

11.5 Fuel Consumption and Combustion of Diesel Engines

The principal reason for the general adoption of diesels in preference to spark-ignition engines has been that they increase the operating range of tanks for a given fuel tank capacity because of their greater thermal efficiency and, therefore, lower fuel consumption. Thus, the minimum fuel consumption of spark-ignition engines run on weak fuel-air mixtures can be as low as 240 g/kWh but in general it is around 300 g/kWh, while the minimum fuel consumption of diesel engines is usually not more than 240 g/kWh and can be only 200 g/kWh. What is more, the differences between the fuel consumption at light loads are much greater than between its minimum values, which are at high loads. This contributes further to the overall fuel consumption of tanks powered by spark-ignition engines being considerably higher than that of their diesel-engined counterparts.

The difference between the fuel consumption of tanks powered by the two types of engines is clearly illustrated by the cross-country tests carried out with a US M48A2 tank powered by the AVI-1790 spark-ignition engine with fuel injection and a M48A2E1 tank powered by the AVDS-1790 diesel, which consumed an average of 9.2 and 6.8 litres per km, respectively (11.22). Given the same fuel tank capacity, this meant that the operating range of the diesel-powered tank was 35 per cent greater than that of the spark-ignition engined tank. Similar differences are demonstrated by the fuel consumption of the spark-ignition and diesel engined versions of the Scorpion light tank, which averaged 0.65 and 0.49 litres per km, respectively, on roads. This again meant that the range of the diesel powered tank was 34 per cent greater, in spite of it being slightly heavier than its spark-ignition engined counterpart.

To some extent the greater operating range of diesel-powered tanks is due to the density of a typical light diesel fuel being 830 kg/m^3 compared with 730 kg/m^3 of

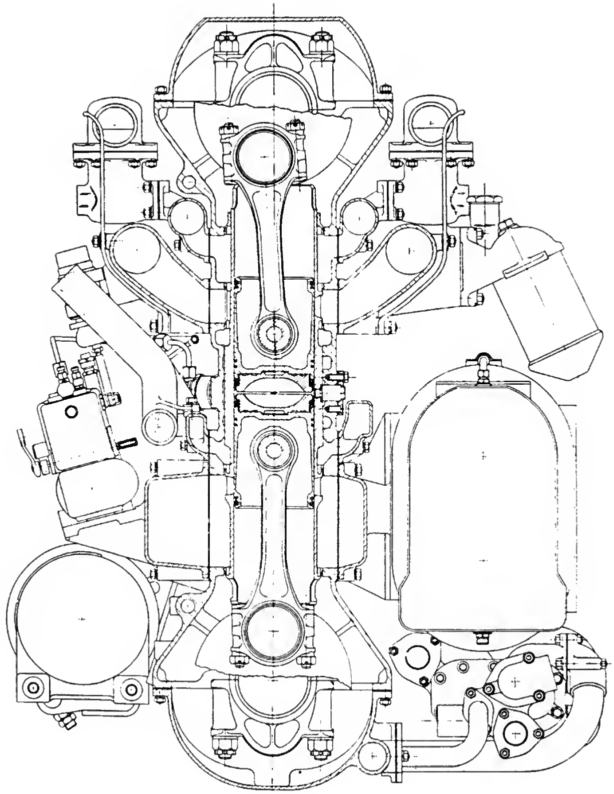


Fig. 11.4 Leyland L.60 opposed-piston two-stroke diesel of the British Chieftain tank. (Leyland Motors)

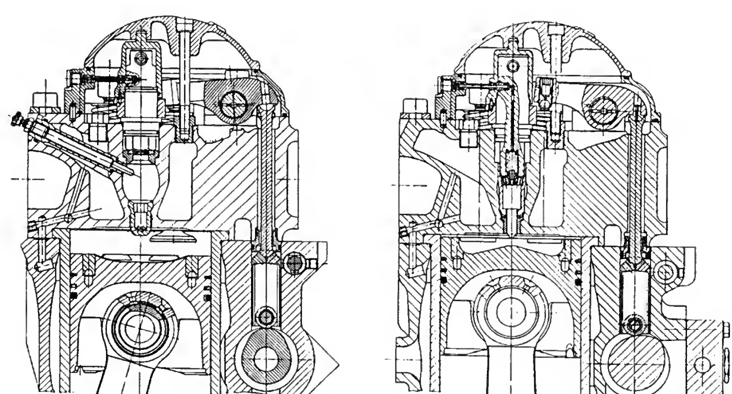


Fig. 11.5 Precombustion chamber (left) of the original version of the MTU MT-883 diesel and (right) the cylinder head of its direct-injection version. (MTU)

80 octane gasoline, although the difference in density is partly nullified by the higher calorific value of gasoline.

Apart from their lower fuel consumption, an important reason for the adoption of diesel engines has been that diesel fuel is less flammable than gasoline. The importance of this increased further since the adoption of diesel engines when it was realised that cells of diesel fuel could contribute to the protection of tanks against shaped charges.

A further reason for the adoption of diesel engines has been their ability to run not only on diesel oil but also on other fuels, such as aviation kerosene and gasoline. This makes it easier to keep diesel engined tanks running when the proper fuel is not available for them because the supply of it has been disrupted.

The ability of diesel engines to run on a range of fuels was clearly demonstrated in 1942, when the Caterpillar Tractor Company successfully modified the Wright G200 air-cooled radial engine into a diesel which proved capable of operating on fuels ranging from crude oil to 100 octane gasoline (11.23). The advantage of diesel engines of being able to operate on more than one fuel was recognised at the time by the US Ordnance Department, which recommended their development partly for that reason (11.24). However, it was only in the 1950s that this advantage was more widely recognised.

As a result a number of diesels was adopted during the 1950s as 'multi-fuel engines'. One of them was the Leyland L.60 diesel which was adopted at the time for the British Chieftain; another was the Hispano-Suiza HS 110 diesel which was adopted for the French AMX-30. Engines such as these were developed in keeping with the policy adopted by NATO in 1957 that fighting vehicles should be powered by multi-fuel engines which, in practice, meant diesels adapted to run on fuels ranging from light diesel oil to aviation gas turbine gasoline (AVTAG or JP 4) and 80 octane gasoline.

Although they were capable of running on different fuels, the operation of diesels on some of them has had its problems. This has been particularly true of their operation on high octane gasoline, combustion of which is difficult to achieve in compression-ignition engines without undue delay. The difficulty of burning even 80 octane combat gasoline is indicated by the fact that its cetane number, the measure of the suitability of fuels for diesel engines, is only of the order of 15 to 20, whereas that of a typical diesel fuel is 47.

To achieve satisfactory combustion of gasoline ignition delay needs to be reduced, which requires the temperature of the air in the cylinder after compression to be as high as possible. This requirement is well met by two-stroke opposed-piston diesels in which combustion takes place between pairs of hot piston crowns. As a result, investigations began in Britain around 1952 into the running of diesels on gasoline as well as other fuels led the Fighting Vehicles Research and Development Establishment to opt in 1958 for a family of 6-cylinder, opposed-piston two-stroke engines, one of which became the Leyland L.60. The decision was backed by about two years' running on a range of fuels of an existing, opposed-piston, two-stroke truck diesel, the Rootes TS-3 (11.25). However, the mechanical layout of the L.60 did not follow that of the TS-3, in which the pistons were connected by rocker levers to a single crankshaft (11.26). Instead, it followed the design of the Junkers Jumo diesel produced in Germany during the 1930s for aircraft, which had two crankshafts geared together and which had long enjoyed a reputation for a high thermal efficiency (11.27). Unfortunately, this type of engine also suffered from thermal stress problems of its complicated cylinder liners and

from the high thermal loading of its pistons. In consequence, the L.60 was afflicted for many years with piston and cylinder liner as well as other problems, which adversely affected its reliability and prevented it for some time from attaining its intended output of 700hp (11.28). In fact, the choice of an opposed-piston engine proved to be unwise, in spite of its merits from the point of view of running on gasoline. Other, more conventional types of diesels could also be run on a range of fuels and they were less troublesome.

One of the engines in the latter category has been the Hispano-Suiza HS 110, a four-stroke 12-cylinder engine with a swirl chamber combustion system. All the MTU diesels, from the MB 837 V-8 of the Swiss Pz.61 tank through the MB 838 V-10 of the Leopard 1 to the MB 873 V-12 of the Leopard 2 have also had indirect injection systems but involving the use of precombustion chambers instead of swirl chambers. Others, like the V-12 diesels of the Soviet tanks, the AVDS-1790 air-cooled diesels of US M60 tanks, the CV 12 diesel developed by Rolls-Royce Motors and produced by Perkins Engines for the British Challenger tank and the Fiat V12 MTCA of the Italian Ariete tank all have direct-injection combustion systems.

Engines with direct-injection generally have a lower minimum specific fuel consumption because of the smaller amount of power being absorbed in pumping air into them and of the lower loss of heat from their open combustion chambers, which also helps cold starting. However, engines with precombustion chambers have been developed to start at low temperatures and the minimum specific fuel consumption of 213 g/kWh of the MB 873 is as low as that of most direct-injection engines. Moreover, engines with swirl and precombustion chambers can use single, instead of multi-hole, injectors which are less vulnerable to clogging, and they tend to have cleaner exhausts, which reduces the smoke signature of tanks powered by them.

11.6 Supercharging of Diesel Engines

At first all types of diesels suffered from the disadvantage of having a significantly lower specific output than spark-ignition engines. But gradually their specific output increased and it not only equalled but exceeded that of any of the spark-ignition engines used to power tanks.

The power output P in watts of any piston engine is described by the following equation:

$$P = \left(n \frac{\pi}{4} D^2 L\right) p N \qquad \ldots\ldots\ldots\ldots \quad 11.1$$

where
- n = number of cylinders
- D = piston diameter, m
- L = piston stroke, m
- p = mean effective pressure, N/m^2
- N = number of firing strokes per second, which equals the number of revolutions per second in the case of two-stroke engines and half the number of revolutions per second in the case of four stroke engines.

The terms within the bracket represent the swept volume of the engine and therefore its specific output, that its power per unit of volume, depends on p and N. Of the two, N is constrained by the maximum possible piston speed, the mean

value of which V_p for a four-stroke engine is given by:

$$V_p = 4 \ L \ N \quad \ldots\ldots\ldots\ldots \quad 11.2$$

The maximum value of the mean piston speed is limited in turn by the breathing capacity of the engine to about 11 and 15 m/s for engines with two and four valves per cylinder respectively. In consequence, once speeds of this order are attained specific output can only be increased further by raising the mean effective pressure. This requires more air being available for combustion and therefore an increase in the mass flow of it into the engine by supercharging.

The maximum gross brake mean effective pressure, or bmep, attained with naturally aspirated four stroke diesels, such as the V-2-34 of the Soviet T-34 tanks, has been 6.3 bar. Some naturally aspirated automotive diesels have had a bmep of about 8 bar but their exhaust smoke levels have been objectionably high and even then its value has fallen short of the 9 bar of spark-ignition engines such as the Rolls-Royce Meteor and the Continental AV-1790, or the 10 bar of the Maybach HL 230.

To increase their bmep above the level attained with naturally aspirated engines, some diesels have been fitted since the mid-1950s with centrifugal superchargers, mechanically driven off the crankshaft of the engine. Centrifugal superchargers were used extensively prior to this with aero engines and their example was first followed by the Mercedes-Benz MB 837 Ba diesel of the Swiss Pz.61 tank. Subsequently mechanically driven centrifugal superchargers were also adopted for the MB 838 CaM diesel of Leopard 1 and more recently for the V-46 diesel of the Soviet T-72 tank.

In the case of the MB 837 Ba the addition of the supercharger increased its maximum bmep from 7.4 bar of the unsupercharged MB837 Aa version to 9.4 bar

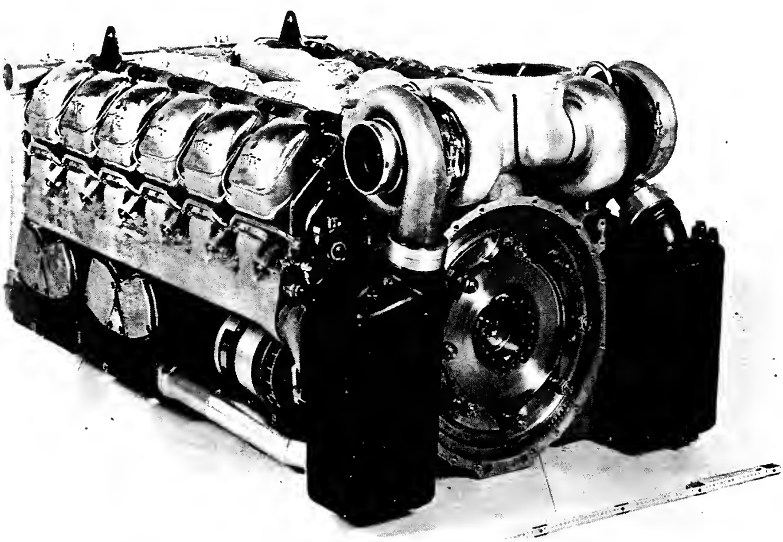


Fig. 11.6 MTU MT-883 twelve cylinder diesel with, in the foreground, its two turbochargers and intercoolers. (MTU)

and the maximum gross hp from 500 to 660 at the same maximum speed of 2200 rev/min. Similar increases in output of about 30 per cent have been obtained with the other engines and they represent the limit of what is economically achievable with mechanically driven centrifugal superchargers.

Any further increase in the specific output of diesels requires them to be fitted with exhaust gas driven turbo-superchargers, which also have the advantage of not needing a mechanical drive. As a result, since the 1950s tank diesels have been generally fitted with turbochargers, starting with the Continental AVDS-1790 and the Hispano-Suiza HS 110. The maximum bmep of these two engines has been 9.5 and 8.5 bar, respectively, and therefore no higher than that of engines with mechanically driven superchargers. But another early example of a diesel with a turbocharger represented by the 750hp Ea-500 version of the MB 837 has already had a maximum bmep of 10.6 bar.

More recently developed diesels with turbochargers, such as the Rolls-Royce/Perkins CV12TCA, Fiat V12 MTCA and MTU MT-883, have still higher maximum bmep of 19.3 to 19.9 bar and an output of 43.1 to 58.9 hp per dm^3 of swept volume, which is already more than the specific output of any of the spark-ignition engines that have powered tanks. Part of the increase in the specific output has been due to the addition of charge air coolers, which increase the density and therefore the mass of the air entering the cylinders of an engine.

However, turbochargers are essentially constant speed machines and they can not be made equally effective over the whole of the wide range of speeds at which tank engines operate. In particular, it is difficult to obtain with them an adequate level of boost pressure at low engine speeds, when the energy of the exhaust gases is low and the turbochargers are working at low speeds. As a result, bmep and therefore engine torque can be relatively low at low engine speeds. Moreover, the acceleration of engines is adversely affected by turbocharger inertia. In consequence, the response of turbocharged engines is generally inferior to that of naturally aspirated engines, or even of engines with mechanically driven superchargers. But they can be considerably smaller, of course, because of their high specific output.

The inferior response of highly turbocharged engines and the adverse effect of it on the acceleration of tanks powered by them was brought out by the experience with the MB 873 Ka-500 diesel which powered the German version of the MBT-70 and the original prototype of Leopard 2. Thus, in spite of its power-to-weight ratio, the acceleration of the latter proved to be inferior to that of Leopard 1, powered by an engine with a mechanically driven supercharger (11.29). This led to a decision to increase the torque of the engine by increasing its bore and stroke and therefore its swept volume from 39.8 to 47.6 dm^3, while keeping its power output at the original level of 1500 metric hp. The outcome was an increase in the maximum torque from 4300 Nm at 1950 rev/min to 4700 Nm at 1600 rev/min, in spite of a simultaneous reduction in maximum bmep from 13.6 to 12.4 bar. In other words, the new engine produced more torque and at a lower speed, which is what is needed for greater vehicle acceleration. At the same time the reduction in bmep meant that less was demanded of the turbocharger, which improved the response of the engine. As a result, when the new, MB 873 Ka-501 engine was fitted in the production version of Leopard 2 its acceleration exceeded that of Leopard 1.

11.7 High Specific Output Diesel Engines

In spite of the problems which it presents, the use of high levels of turbocharging has been pursued further in order to increase even more the specific output of diesels. The most obvious way of achieving this is to proceed beyond simple turbochargers to two-stage turbocharging with inter- and after-cooling, but this involves considerable complexity.

The inability of the simple, fixed-geometry turbochargers to provide an appropriate level of boost pressure over the whole of the speed range of the engine, which results either in a relatively low torque at low speeds or in power being restricted at high speeds, can be circumvented by the use of variable geometry turbocharges. But while these make it possible to keep bmep and therefore torque high at both high and low engine speeds, they also introduce more complexity. Nevertheless, a variable geometry turbocharger was already developed in the mid-1970s for an experimental version of the Teledyne Continental AVCR-1360 diesel and raised its output from 1500 to 1750hp.

An alternative method of increasing bmep and torque at low engine speeds is to use a mechanically driven positive displacement blower in series with a simple turbocharger. This solution was adopted for the AVCR-1360-2, which powered the General Motors prototype of the US M1 tank (11.30). A similar combination of a turbocharger working in series with a positive displacement blower has been used with the General Motors two-stroke uniflow diesels such as the 12V 71T used in the Vickers Mark 3 battle tank. But in this case the positive displacement blower has been the scavenge blower which forms an integral part of two-stroke diesels.

In addition to its two-stage supercharging system, the Teledyne Continental AVCR-1360 also incorporated variable compression ratio pistons, which enabled

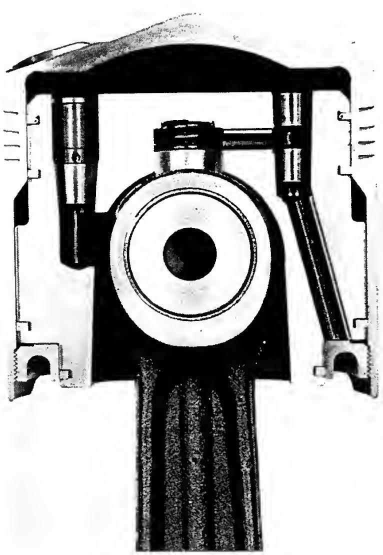


Fig. 11.7 Sectioned piston of the Teledyne Continental variable compression ratio diesels. (Teledyne Continental Motors)

it to have for several years a higher specific output than any other tank diesel. In fact, it had a maximum bmep of 24.3 bar and an output of 67.3 hp, or 50kW, per dm^3.

The variable compression ratio pistons were originally developed in the 1950s by the British Internal Combustion Engine Research Association and consisted in essence of an inner part pin-jointed to the connecting rod and of an outer shell which could move relative to the inner part to alter the overall height of the piston assembly and consequently the compression ratio. The relative position of the two parts of the piston was controlled, through a relief valve, by the pressure of the oil trapped between them. This resulted in the engine having a high compression ratio, as required, for starting and at light loads and a lower compression ratio at full load, so that its power increased without a corresponding increase in the peak cylinder pressure.

The variable compression ratio piston was taken up in the United States by Continental Motors and in 1960 it was applied in a new Continental V-12 air-cooled diesel, allowing its output to be increased from 550hp of the original AVDS-1100 version to 1100hp of the variable compression ratio AVCR-1100. Eventually the AVCR-1100 was rated at 1475hp and in 1964 it was adopted for the US prototypes of MBT-70. This led to it being developed into the AVCR-

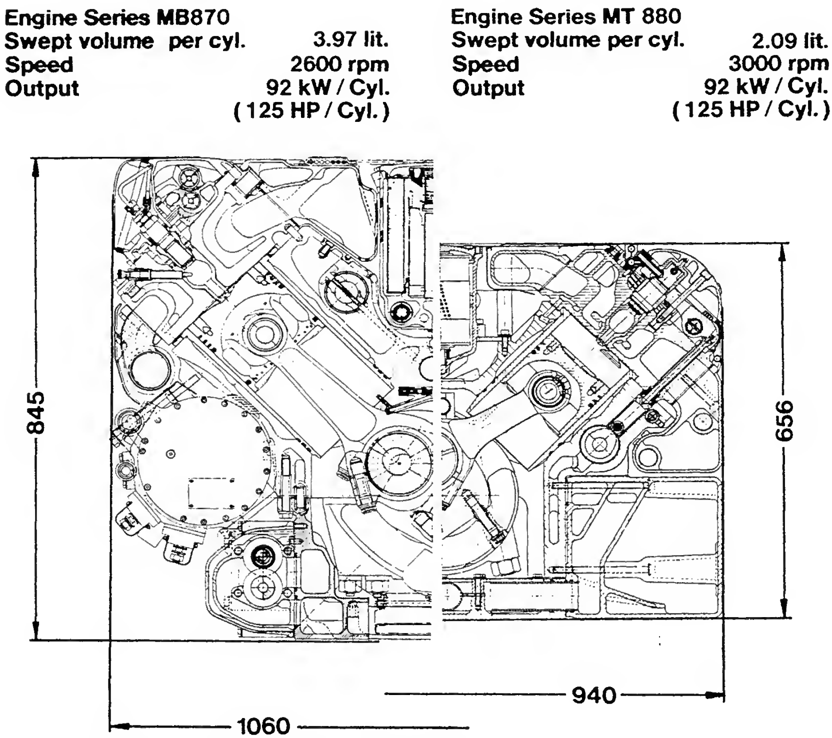


Fig. 11.8 Comparison of the size of the MB 873 engine of Leopard 2 and of the more recently developed MT-883 engine (dimensions in millimetres). (MTU)

1100-3A, with a swept volume increased from 18.3 to 22.3dm^3, which was rated at 1475hp in the MBT-70 but only 1250hp in the XM803 tank. It was then transformed into the AVCR-1360-2 of 1500hp, which powered the General Motors XM-1 prototype.

The variable compression ratio pistons undoubtedly offered the advantage of a high specific output without a corresponding increase in peak cylinder pressure. But they also introduced complexity where it is least wanted in engines and resulted in variations in the geometry of the combustion space, which made it difficult to achieve good combustion over the whole of the engine operating range. This manifested itself in exhaust smoke, particularly at starting, and in a higher specific fuel consumption than that of more conventional diesels. Moreover, the bmep and therefore torque of the AVCR-1100 and AVCR-1360 engines fell off rapidly as their speed decreased, which was very undesirable from the vehicle point of view. All this handicapped the AVCR-1360-2 in the competition for the engine of the US M1 tank and when it failed to be adopted in 1976 interest in engines with variable compression ratio pistons waned rapidly.

In the meantime an entirely different approach to increasing the specific output of tank engines was adopted in France in the mid-1970s in the form of the Suralmo-licence Hyperbar turbocharging system. This was applied to the Poyaud 520 V-8 diesel produced by the Societé Surgerienne de Constructions Mécanique, increasing its output to 800 metric hp. compared with 270 metric hp of its naturally aspirated version and 480 metric hp of the version with conventional turbo-charging and charge air cooling. The output of the V8 520 S3 engine was subsequently raised further to 1200 metric hp. After its swept volume was increased from 13.96 to 16.47 dm^3 it was developed into the V8 X 1500 engine, which was adopted for the AMX Leclerc (11.31). This engine has since become known as the UNI Diesel UD V8 X 1500 and it develops 1500 metric hp at 2500 rev/min, which amounts to no less than 91 metric hp, or 67kw, per dm^3; it also has an equally high maximum bmep of 34.9 bar.

The Hyperbar system is based on the use of a high pressure turbocharger driven not only by the exhaust gases but also by the additional energy supplied by a gas turbine type combustion chamber operating in parallel with the engine. The turbocharger specially developed for the UD V8 X 1500 engine by Turbomeca provides a compression ratio of 7.9:1 and in its second TM 307 B version has a single-stage centrifugal compressor driven by a two-stage axial-flow turbine.

Apart from the remarkably high bmep and specific output, the Hyperbar system also provides the UD V8 X 1500 engine with good torque-speed characteristics and a rapid response, because of the speed with which extra energy can be supplied to the turbine of the turbocharger, and this makes for good vehicle acceleration. It also provides good cold starting, particularly at low ambient temperatures, because the turbocharger can be easily started by itself, like a gas turbine, and can then make hot air available for the starting of the engine. On the other hand, the Hyperbar system greatly increases the complexity and cost of diesel engines. It also increases their fuel consumption, mainly because of the extra fuel burnt in the combustion chamber, although test bed results obtained with the UD V8 X 1500 engine indicate a minimum specific fuel consumption of 225 g/kWh, which is comparable to that of other diesels. Moreover, although the UD V8 X 1500 engine has a much higher output per unit of swept volume than other diesels its output per unit of total power unit volume is not greater than that of some more conventional diesels, such as MTU's MT-883.

11.8 Thermally Insulated Diesel Engines

Apart from increases in bmep and improvements in their design, the output of tank engines can also be increased in relation to their total volume by reductions in the size of the cooling systems. As it is, cooling systems of recently produced liquid-cooled engines of 1500hp have a volume of the order of 1 m^3, which means that they account for about 40 per cent of the total volume of the engine installations. What is more, the fans of the existing cooling systems absorb 10 to 15 per cent or more of the gross engine output, although some of the power consumed by them as well as part of the volume of cooling systems are due to the need to cool the transmission oil as well as the engines.

The size of the cooling systems could be reduced if the heat flow to the coolant were restricted and this can be done by insulating parts of engines, such as cylinder heads, cylinder liners and piston crowns from the hot combustion gases. The most suitable form of insulation is provided by ceramic materials and in particular stabilised zirconia, which has a low thermal conductivity and a low coefficient of thermal expansion close to that of cast iron.

The possibility of drastically reducing the heat transfer from the combustion gases to the engine by the use of ceramic insulating materials has given rise to the concept of the adiabatic diesel engine. This engine would operate at higher temperatures than conventional diesels and not only dispense with a cooling system but also offer greater thermal efficiency, because less of the energy released by the combustion of fuel would be lost (11.32). However, a truly adiabatic engine, that is one with no heat transfer at any time between the gases and the surrounding walls, is not practicable and a significant increase in thermal efficiency can only be achieved by turbo-compounding. This involves the use of the additional energy present in the exhaust gases of a thermally insulated engine to drive a turbine geared to the engine crankshaft, which increases the power produced by the engine but which also increases its complexity.

On the other hand, even a partial reduction of the heat transfer to the coolant could result in a significant reduction in the size of the cooling system, which would be sufficient in itself to justify the development of tank engines with thermal insulation. Such engines would also be quieter, because the higher temperature of their combustion chambers would reduce ignition delay and it should also improve their ability to operate on low cetane fuels.

The perceived advantages of thermally insulated or quasi-adiabatic engines led the US Army to take up their development for tanks during the early 1980s (11.33). In particular, it awarded a contract in 1984 to the Cummins Engine Company for the development of a thermally insulated diesel as part of its Advanced Integrated Propulsion System Program.

11.9 Gas Turbines

No sooner had diesels become generally accepted as tank engines than an alternative to them began to emerge in the form of the automotive gas turbines, which have since become their principal competitors.

Study of the application of gas turbines to tanks began as early as 1944 in Germany, where the world's first gas turbine powered aircraft, a Heinkel He 178, flew in 1939. The German work had not advanced beyond the preliminary design of a gas turbine of about 1000hp when it was ended by the defeat of Germany in 1945 (11.34). However, the potential advantages of gas turbine engines of a high

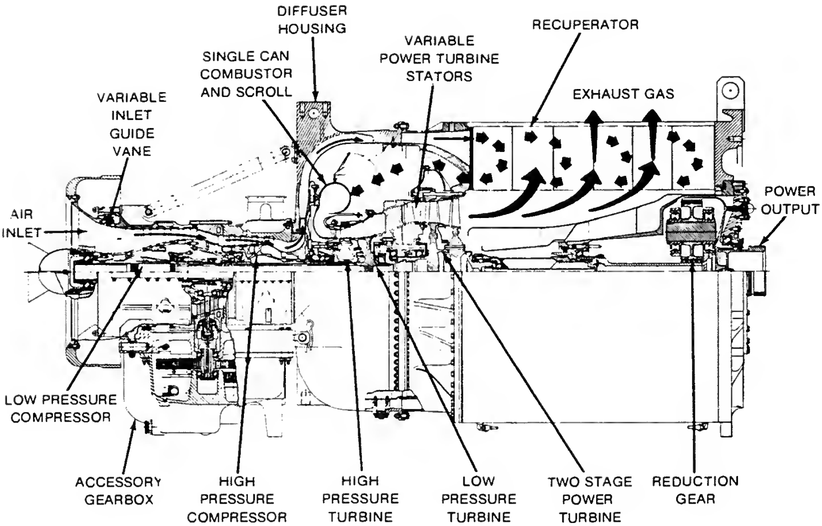


Fig. 11.9 AGT-1500 gas turbine which powers the US M1 tank. (Avco Lycoming)

specific output and favourable torque-speed characteristics attracted wider attention after the Second World War. But their disadvantage of high fuel consumption and the need for it to be reduced before they could be used satisfactorily in tanks were also noted (11.35).

The high fuel consumption was made evident by the first gas turbine built specifically for tanks, in Britain, by C A Parsons & Company and installed in 1954 in a Conqueror heavy tank chassis. Designated Parsons Unit 2979, this engine consisted of a single-stage centrifugal compressor driven by a single-stage axial-flow turbine and of a two-stage power turbine and was rated at 655hp. The next Parsons' gas turbine, Unit 2983, was rated at 910hp but neither engine advanced beyond trials and no more gas turbines were built subsequently in Britain for tanks.

No gas turbine was built for tanks elsewhere until the 1960s, when their development was taken up in the United States. It began in 1961 when the US Army sponsored the competitive development of a 600hp gas turbine by the Solar Aircraft and Ford Motor Companies. The designers of the resulting Solar T-600 engine attempted to achieve an adequately low fuel consumption by the use of a twin-drum regenerator in conjunction with a six-stage axial flow compressor driven by a two-stage axial-flow turbine and a single-stage power turbine (11.36). The designers of the Ford 705 engine adopted a much more complex two-spool, three shaft configuration which had already been chosen for the smaller, 300hp Ford 704 experimental truck engine (11.37). It incorporated two stages of compression, the first being provided by the low-pressure spool consisting of a centrifugal compressor driven by a single-stage axial flow turbine and the second by the high-pressure spool with another centrifugal compressor driven by a radial,

inward-flow turbine. It also incorporated intercooling of the air between the two stages of compression, a plate-type recuperator between the high pressure compressor outlet and the primary combustion chamber located ahead of the turbine of the high pressure spool. There was also a secondary or reheat combustion chamber between the exit from the high-pressure spool turbine and the single-stage power turbine, which was uniquely located between the high and low-pressure spool turbines. For all this, the Ford 705 as well as the Solar T-600 failed to establish an overall advantage over diesel engines and their development was abandoned without either being tried in a tank, although a Solar Saturn gas turbine which had been designed for other purposes was installed in a T95 tank for demonstration purposes.

However, the US Army persevered and in 1965 placed a contract with the Lycoming Division of Avco Corporation for the development of another gas turbine. This became the AGT-1500, or the Army Ground Turbine of 1500hp, which was originally considered for the MBT-70 and which was adopted in 1973 by Chrysler's Defense Division for its XM-1 prototype. After the latter was accepted by the US Army in 1976 the AGT-1500 was put into production for the M1 tank and began to enter service with it in 1980.

The designers of the AGT-1500, like those of the Ford 704 and 705 gas turbines, attempted to reduce its fuel consumption to a competitive level by a combination of a high overall pressure ratio of 14.5:1 provided by a two-spool, three-shaft configuration with a plate-type, cross-flow recuperator with an efficiency of about 72 per cent. However, they dispensed with the secondary combustion chamber and by making the two compressor spools as well as the two-stage axial-flow power turbine and the cylindrical recuperator coaxial they obtained a more compact layout. On the other hand, they adopted axial flow compressors instead of the more robust centrifugal compressors. Thus, the low-pressure spool incorporated a five-stage axial flow compressor and the high pressure spool contained a compressor with four axial stages followed by a centrifugal stage, each spool being driven by a single-stage axial-flow turbine.

To help reduce its fuel consumption further, the AGT-1500 was made to operate with a higher turbine inlet temperature of 1190°C than earlier ground vehicle gas turbines to improve part-load efficiency, and variable angle stators were also adopted for the first stage of the power turbine.

The design of the AGT-1500 appeared at first to have overcome the problem of the high fuel consumption of gas turbines, for when it began to be tested in 1967 its minimum specific fuel consumption was said to be 225 g/kWh, which is as low as that of diesel engines (11.38). But in 1971, when more experience had been acquired with two prototype engines, the claims became somewhat less optimistic. The minimum specific fuel consumption was given as 274 g/kWh, but it was still expected that it would be brought down to 255 g/kWh (11.39). In fact, when the AGT-1500 was put into production its minimum specific fuel consumption turned out to be 290 g/kWh, which is comparable to that of the spark-ignition gasoline engines that had been discarded in favour of diesels because of their higher fuel consumption. Moreover, at light loads the fuel consumption of the AGT-1500 has been much higher in relation to that of diesels than at its minimum (11.40).

Test bed figures of fuel consumption established with bare engines are not entirely fair to gas turbines because of the lower parasitic losses of their vehicle installations and in particular because they lose far less power to cooling fans than piston engines. A more objective basis of comparisons is therefore fuel consumption per unit of net sprocket power and in 1971 this was claimed to be lower than that of the contempo-

rary diesels. But subsequently it turned out to be 468 g/kWh at full load, compared with 280 to 360 g/kWh of diesel power packs of similar power. At part load the differences have again been considerably greater and the overall fuel consumption of the M1 tank powered by the AGT-1500 has been generally assessed to be twice what it would be if it had been powered by a diesel.

The higher fuel consumption of a tank such as the M1 exacerbates the problem of supplying tank units with fuel under battlefield conditions and nullifies the advantages of lighter weight and smaller size of gas turbines, because tanks powered by them need to carry more fuel for a given operating range or endurance. Gas turbines have also been more expensive to produce, their cost being estimated at up to twice the cost of comparable diesels.

On the other hand, gas turbines enjoy several other advantages over diesels. They include much easier starting at low temperatures, insensitivity to the cetane or octane rating of the fuel, much lower consumption of lubricating oil, virtually no visible smoke emissions and quieter operation, which not only reduces the acoustic signature of tanks powered by them but also makes them less fatiguing for the crews. Compared with diesels, gas turbines require more air for combustion, typically 18 instead of 6 kg/kWh, which implies the need for larger air cleaners. But they require considerably less cooling air. Consequently, the total air mass flow is less than with diesels, being of the order of 30 kg/kWh compared with about 45 kg/kWh of the diesels. This means that they need smaller air inlet and exhaust louvres.

By analogy with aircraft experience, gas turbines have been claimed to require less routine maintenance than piston tank engines and to allow longer periods of operation between overhauls. Evidence of this and of the reliability of gas turbines in tanks is still limited but the experience of the US Army with its gas turbine powered M1 tanks has shown that a greater percentage of them is likely to be available for operation at any given time than of its diesel powered M60 tanks.

Claims have also been made that gas turbines designed more recently than the AGT-1500 were overcoming the problem of high fuel consumption which has hitherto handicapped gas turbines and that tanks powered by them would consume less fuel overall than their diesel engined counterparts (11.41). Some of the claims to this effect were based on the development in the United States of the Garrett GT-601 gas turbine, which was designed between 1972 and 1976 and which first ran in 1977. The GT-601 was designed for use in heavy trucks but it was also tried in several armoured vehicles, starting in 1981 with the US XM723 Mechanized Infantry Combat Vehicles and following with the M48, Chieftain, AMX-30 and T-55 tanks.

As it was designed originally for commercial truck operation, the GT-601 was simpler and more robust than the AGT-1500, which was developed from the basis of aircraft gas turbines and of which there was even an aircraft version, the PLT-27. Thus, the gas generator section of the GT-601 contained a single spool consisting of a two-stage centrifugal compressor driven by a single, inward flow radial turbine but the power section contained a two-stage axial-flow turbine with variable angle stator blades in both stages to improve part-load efficiency and to provide engine braking. The overall pressure ratio of the GT-601 was only 7:1 and at 1038°C the turbine inlet temperature of its 640hp truck version was significantly lower than that of the AGT-1500. But it did have a contra-flow recuperator with an efficiency of about 83 per cent and its minimum specific fuel consumption was 237 g/kWh, which represented a significant improvement on the AGT-1500. In fact, the specific fuel consumption of the GT-601 was about as low as that of diesel engines,

except at light loads, and the overall fuel consumption of vehicles powered by it was estimated to be only 10 per cent higher than that of their diesel-powered counterparts. But, because of its more robust design and of its relatively bulky recuperator, the GT-601 was approximately twice as heavy and large in relation to its power as the AGT-1500. It did not, therefore, have an advantage over diesels so far as weight and volume are concerned. Because of this and the fact that its fuel consumption was still higher, the GT-601 did not prove a superior alternative to diesels as a tank engine. This was also true of its uprated, military version which developed 750hp but at the cost of a higher minimum specific fuel consumption of 256 g/kWh.

The most recent gas turbine designed for tanks forms part of the General Electric LV 100 power pack developed under a contract awarded by the US Army in 1984 as part of its Advanced Integrated Propulsion System Program. The goal set for it has been to deliver approximately the same amount of power at the sprockets as the AGT-1500, that is 1050hp or 783 kW, but to consume 40 per cent less fuel. To achieve this together with a 40 per cent reduction in the air mass flow it was designed to operate with a higher turbine inlet temperature as well as having an efficient recuperator.

The LV 100 power pack incorporating the gas turbine was also to be 33 per cent smaller than that based on the AGT-1500, which meant that it was to occupy, together with the fuel tanks, a total volume of not more than 5.5 m^3, instead of 8.4 m^3. The saving of 2.9 m^3 in the volume occupied by the power pack implies that if it were exploited in the design of a tank of the M1 type the tank's hull could be significantly smaller. In particular, it could be about 1.2m shorter, which would reduce its weight by more than 2 tons. However, not all of the potential saving in hull volume could be attributed to the LV 100 power pack since 1.3 m^3 could also be saved by mounting the AGT-1500 transversely, instead of longitudinally.

11.10 Hybrid Power Units

Although they differ in many ways, the characteristics of gas turbines and of diesels are in some respects complementary and this has led to the development of hybrid power units which combine elements of both types of engines in order to exploit their individual advantages and to overcome their particular shortcomings.

The most direct way of combining the two types of engines is to use one of each in a twin-engine power unit. This has been done in the Swedish S-tank, which has been powered by a Rolls-Royce K.60 diesel and a Boeing 553 gas turbine geared to a common output. Before it was adopted in the S-tank, an analogous CODAG, or Combination of Diesel and Gas Turbine, installation had been adopted for warships, to which it offered the advantages of the economy of the diesel for cruising and of being able to provide the additional power required for limited periods of time from the relatively light weight and compact gas turbine. Similarly, in the S-tank the diesel is meant to be used alone under normal running conditions, when the power requirements of tanks are low, and the gas turbine is to be switched on only for the relatively infrequent periods when large amounts of power are required. Such an arrangement not only exploits the efficiency of the diesel and the high specific output of the gas turbine but also minimises the inefficiency of the latter by confining its operation to peak power periods. This has been particularly important in view of the fact that the Boeing 553 is a simple, two-shaft turbine without a heat exchanger and its part-load efficiency is, therefore, low.

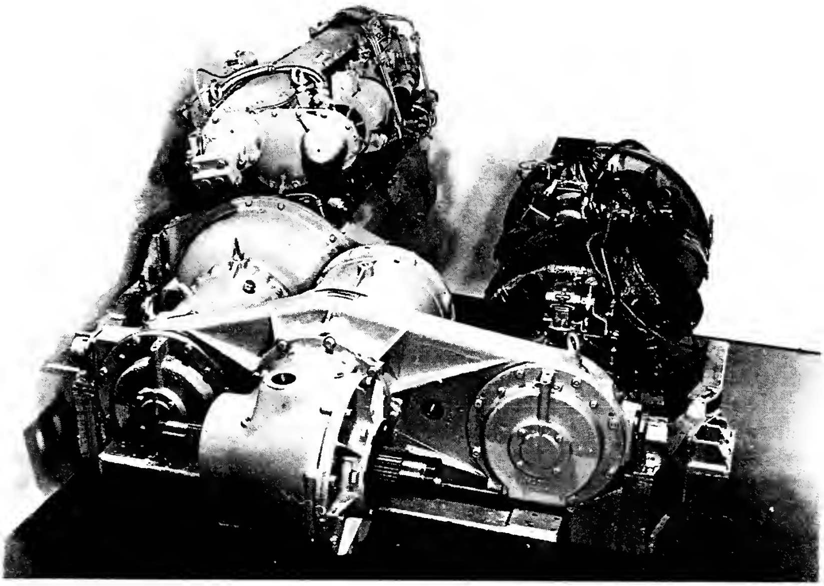


Fig. 11.10 Twin-engine power pack of the Swedish S-tank with, left, a Rolls-Royce K.60 diesel and, right, a Boeing 502-10MA gas turbine.

Apart from the usual advantage of being easy to start under cold weather conditions, the gas turbine of the S-tank can also be used as a starter for the diesel when the temperatures are very low and the starting of diesel engines is a problem. The gear train coupling the two engines also allows either to be used by itself to drive the tank, which halves the risk of it being immobilised by an engine failure.

However, the combination of a gas turbine with a diesel is more complex than a single engine of either kind and, like other twin-engine installations, uses more space. It is not, therefore, as attractive in practice as it is in theory. But even if the example of its hybrid power unit has not been followed, the S-tank was the first tank to go into service with a gas turbine and to this extent set a lead.

A more gradual approach to combining the characteristics of a gas turbine with those of a diesel is provided by gearing the turbocharger of a diesel engine to its crankshaft, instead of allowing it to float freely. This results in a compound engine in which some of the power provided by the engine is generated at the turbine of the turbocharger and is added to the power coming out of the crankshaft of the engine. The additional power supplied by the turbocharger turbine represents more energy being extracted out of the exhaust gases, which can result in a significant improvement in the efficiency of the engine, particularly when there is more energy available in the exhaust gases, as it is in thermally insulated engines.

Unfortunately, simple, fixed-ratio gearing between the turbocharger and the crankshaft tends to result in unsatisfactory part-load performance. To avoid this the gearing needs to be variable. Such gearing was, in fact, used in the pioneer

Napier Nomad compound engine developed in Britain during the late 1940s for aircraft propulsion, which was claimed to have the highest thermal efficiency ever achieved in an aero engine (11.42). But variable speed gearing makes the compound engine more complex. A similar disadvantage accompanies alternative methods of improving part-load performance, such as the use of a variable geometry turbocharger turbine or of a separate, low-pressure power turbine downstream of the turbocharger left free to float, as in conventional turbocharged engines.

Compound engines with a free floating turbocharger and a separate power turbine can be elaborated further by replacing the fixed ratio gears between the power turbine and the crankshaft by variable speed gearing or by providing the power turbine with variable angle stators. However, while such elaboration might improve part-load performance it also makes turbo-compound engines even more complex and costly. It is not surprising, therefore, that the first compound engine to be developed for tanks has been of a much simpler nature with two turbochargers geared to the crankshaft by fixed ratio gears. The engine is the 10ZF22WT, a V-10 two-stroke, uniflow, air-cooled diesel developed by Mitsubishi Heavy Industries for the Japanese Type 74 tank which has a crankshaft geared turbocharger for each bank of five cylinders. The aim of the compounding in this case has been to supply additional power to the turbochargers at maximum engine output rather than to extract power from them and one of its major benefits has been to make redundant the scavenge blowers which are generally required by two-stroke engines (11.43).

Given a separate power turbine, as in some of the more elaborate of the compound engines, there is an alternative to gearing it to the engine crankshaft, which is to uncouple it from the latter and use it to generate all the output. In that case the piston engine becomes confined to the role of a gas generator and the free power turbine endows the resulting power unit with torque-speed characteristics as good as those of gas turbines, from the vehicle point of view. This, together with its high pressure ratio and more rapid response, made the gas generator engine an attractive alternative, in principle, to the gas turbine.

In consequence, a gas generator engine began to be developed for tanks in 1950, when the US Army placed a contract for one with the General Electric Company. Called the Orion, the engine consisted in essence of a two-stroke, opposed-piston, six-cylinder, air-cooled diesel driving a centrifugal compressor and of a single-stage axial-flow turbine which was mechanically free of the diesel unit and provided the whole output of 600hp. Two such engines were built but their development was terminated in 1955 before either could be tried in a tank (11.44).

No other attempt appears to have been made to develop a gas generator engine for tanks. Although attractive in principle, this type of engine has not offered sufficient, if any, advantage over the gas turbine which it most closely resembles. It also suffers from the basic disadvantage of being complicated because it contains all the elements of a reciprocating, piston engine as well as turbo-machinery.

11.11 Rotary Engines

In spite of the successful use of spark and compression-ignition piston engines, several attempts have been made to develop an alternative type of positive displacement internal combustion engine with rotary instead of reciprocating motion of its principal working elements. The most successful of them has been the rotary engine developed in Germany by F Wankel in collaboration with the NSU company, which first took practical form in 1958 with the adoption of an epitrochoidal

chamber in a stationary housing. By 1965 the NSU-Wankel rotary engine advanced to the stage of a 55hp model being produced to power the NSU Spider car and this was followed by the production of a rotary engine powered Mazda car in Japan. In the meantime the Curtiss-Wright Corporation acquired a licence for the NSU-Wankel type of engine and began to develop larger versions of it in the United States (11.45). Moreover, three years after building their first rotary engine in 1959 Curtiss-Wright started work on a stratified charge version by adding a diesel-type injection nozzle adjacent to the spark plugs and dispensing with the carburettor used with the earlier engines (11.46). The development of the stratified charge version was prompted by the military requirements for engines capable of operating not only on high octane gasoline but also on less volatile fuels, such as JP-4, and followed the example of stratified charge piston engines with fuel injection and spark ignition set by Texaco TCCS, Ford Proco and Honda CVCC engines.

By the time Curtiss-Wright built the first of their stratified charge engines the British Army had become interested in rotary engines and in 1965 placed a contract with Curtiss-Wright for the RC2-60U10 stratified charge engine of 180hp. In addition it acquired two RC-60U5 carbureted engines which were tested between 1967 and 1969 in a FV 432 tracked armoured carrier and in a Ferret wheeled scout car. The British Army also sponsored work at Rolls-Royce on rotary engines, which led to a decision in 1964 to investigate the feasibility of a diesel version of them. This led to the development by Rolls-Royce of a two-stage rotary diesel, which embodied high and low pressure rotors working in series. Two different experimental engines of this type, the R1 and the R3 of 180hp were built and tested by 1970 and a larger 2-R6 engine with two banks, which was to develop 350hp, was designed for use in armoured vehicles (11.47).

The rotary diesels were expected to have the advantage over reciprocating engines of smaller size, lower weight, fewer parts and smoother running and over gas turbines of lower fuel consumption. However, rotary engines suffer from a

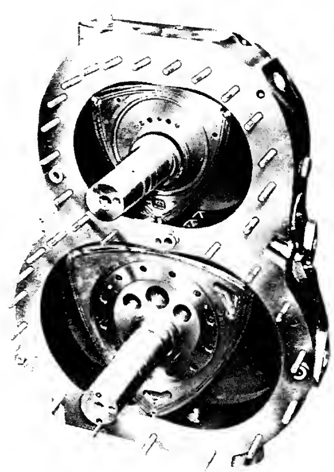


Fig. 11.11 Rolls-Royce two-stage R1 rotary diesel. (Rolls-Royce Motors)

major disadvantage, which is that satisfactory gas sealing is inherently more difficult to achieve between their rotors and chamber walls than it is between the pistons and cylinders of reciprocating engines. Another disadvantage is the uneven heating of the housings of rotary engines, which arises out of combustion taking place in one part of the chamber while others are cooled by the incoming air. Moreover, although rotary engines themselves have been smaller in relation to their power than most reciprocating diesel engines, when considered together with their cooling systems, auxiliaries and the fuel tanks they have not shown sufficient advantage in terms of volume over the reciprocating engines so far as tanks are concerned. They also required considerable further development before they could be considered for use in the field. In consequence, the British Army abandoned the development of rotary diesels after 1972 and in Japan the Yanmar Diesel Co. also did not proceed with their two-stage rotary diesel beyond tests. Similarly, none of the major car manufacturers who had tested them showed further interest in rotary engines after the early 1970s, except for Toyo Kogyo who continued to use them in some of the Mazda cars.

The only NSU-Wankel type of rotary engine which has continued to be developed for military purposes has been the stratified charge version with direct fuel injection into the chamber and with spark ignition. Further work on it by Curtiss-Wright during the 1970s was sponsored by the US Navy with a view to its possible use in the amphibious Landing Vehicle Assault (LVA) which was being proposed at the time for the US Marine Corps. This led to the four-rotor RC4-350 of 1500 hp and then to the twin-rotor versions of it, the RC2-350 of 650hp, when the LVA concept was shelved in 1980 in favour of the less ambitious LVT(X) amphibious armoured vehicle.

In 1984 the development of rotary engines was taken over from Curtiss-Wright by John Deere Technologies International, who have continued to develop them under the name SCORE – an acronym for Stratified Charge Omnivorous Engine – which is intended to indicate the engines' ability to operate on fuels ranging from combat gasoline to diesel fuel. In particular, John Deere continued to develop the RC2-350 engine under the new designation of Model 2116R of the 580 series, the 580 standing for the displacement per rotor of 5.8 dm^3. This engine has continued to be developed for the US Marine Corps in a turbocharged form which produces 750hp at 3600 rev/min and is stated to have a minimum specific fuel consumption of 237 g/kWh. On the strength of the performance of this version the turbocharged stratified charge rotary engine is claimed to be competitive with direct-injection reciprocating diesels in terms of fuel consumption as well as being lighter, smaller, simpler and smoother running (11.48). At the same time the cost of a four-rotor 580 series engine of 1500hp has been claimed to be equal to only one third of the cost of the AGT-1500 gas turbine. However, the total volume of such an engine would be no smaller than that of a well-designed conventional diesel engine, such as the MTU MT 883, of the same power. What is more, even if the minimum specific fuel consumption of stratified charge rotary engines proves to be close to that of conventional diesels, it remains to be seen what is the overall fuel consumption of vehicles powered by them and how reliable they are.

11.12 References

11.1 A G Stern, *Tanks 1914-1918*, Hodder and Stoughton, London, 1919, p.123.

11.2 H R Ricardo and H S Glyde, *The High-Speed Internal-Combustion Engine*, Blackie, London, 1941.

11.3 R E Jones, G H Rarey and R J Icks, *The Fighting Tanks since 1916*, National Service Publishing Co., Washington, 1933, pp.168-169.

11.4 W Esser, *Die Panzerkampfwagen unserer Gegner*, A.T.Z., Vol.46, No.17/18, 25 September 1943, pp.399-426.

11.5 W Esser, *Dokumentation über die Entwicklung und Erprobung der ersten Panzerkampfwagen der Reichswehr*, Krauss-Maffei, Munich, c.1979, p.A.5.6.

11.6 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, pp.74-83 and 143-166.

11.7 J Bingham, *Australian Sentinel and Matildas*, AFV/Weapons Profile No.31, Profile Publications, Windsor, 1971.

11.8 R E Jones, et al., op.cit., pp.157-158 and 194-195.

11.9 R J Icks, 'Engines for Tanks', *SAE Journal*, Vol.51, No.7, July 1943, pp.41 and 54.

11.10 W Wagner, *Continental, Its Motors and Its People*, Aero Publishers, Fallbrook, 1983, pp.124-130.

11.11 T Hara, *Japanese Medium Tanks*, AFV/Weapons Profile No.49, Profile Publications, Windsor, 1972.

11.12 F R Banks, *The Aviation Engine*, Proceedings of the Institution of Mechanical Engineers, Vol.162, No.4, 1950, pp.437-439.

11.13 *Military Vehicle Power Plant Cooling*, AMCP 706-361, US Army Materiel Command, Washington, 1975, p.1-4.

11.14 J P Chiou, *Engine Cooling Systems for Military Combat/Tactical Vehicles* SAE Paper No.750030, Society Automotive Engineers, Warrendale, 1975, p.14.

11.15 J H Pitchford, 'Engine Research and Development as a Service to Industry : A Personal Experience', *Chartered Mechanical Engineer*, Vol.2, No.1, January 1955, pp.34-40.

11.16 T Hara, op.cit.

11.17 W Wagner, op.cit., pp.90-91.

11.18 R P Hunnicutt, op.cit., pp.152, 525 and 526.

11.19 R J Icks, op.cit., p.56.

11.20 H H Haas and E R Klinge, *The Continental 750-Horsepower Air-Cooled Diesel Engine*. SAE Paper No.47, Society of Automotive Engineers, New York, 1957.

11.21 J H Brewer, *A Jaguar in Military Camouflage*, Proc.Inst.Mech.Engrs., Vol.191, 18/77, 1977.

11.22 R P Hunnicutt, *Patton*, Presidio Press, Novato, 1984, pp.151-152.

11.23 R P Hunnicutt, *Sherman*, op.cit., p.167.

11.24 R J Icks, idem.

11.25 H L Troughton, *The United Kingdom Approach to the Problem of Multi-Fuel Engines*, Symposium on Multi-Fuel Engines, Fighting Vehicles Research and Development Establishment, Chobham, 1959.

11.26 E W Coy, *The Opposed-Piston Two-Stroke Oil Engine as a Multi-Fuel Unit*, Symposium on Multi-Fuel Engines. Fighting Vehicles Research and Development Establishment, Chobham, 1959.

11.27 D R Pye, *The Internal Combustion Engine*, Vol.II, Oxford University Press, London, 1934, p.289.

11.28 'Chieftain – So Often Let Down by its Engine', *Diesel Engineering*, Autumn 1978, pp.150-151.

11.29 W J Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, p.283.

11.30 J R Grundy, L R Kiley and E A Brevick, *AVCR-1360-2 High Specific Output Variable Compression Ratio Diesel Engine*, SAE Paper 760051, Soc. Automotive Engineers, Warrendale, 1976.

11.31 M R Le Merer, 'Moteurs Diesel à Tres Haut Rapport de Suralimentation', *Ingenieurs de l'Automobile*, No.4, May 1980, pp.61-69.

11.32 R Kamo and W Bryzik, *Adiabatic Turbocompound Engine Performance Prediction*, SAE Paper 780068, Soc. Automotive Engineers, Warrendale, 1978.

11.33 P C Glance and R Mount, *Engine Research, Development and Acquisition Strategy*

for US Army Ground Vehicles, SAE Paper 830674, Soc. Automotive Engineers, Warrendale, 1983.
11.34 R H Bright, *The Development of Gas Turbine Power Plants for Traction Purposes in Germany*, Proc.Inst.Mech.Engrs., Vol.157, 1947, pp.375-382.
11.35 R M Ogorkiewicz, 'Gas Turbines for Tanks?', *Armor*, Vol.61, No.5, September-October 1952, pp.16-19.
11.36 R Rayle, G Graves and A F Johnson, *The Army-Navy 600hp Gas Turbine Program*, SAE Paper 450 B, Soc. Automotive Engineers, New York, 1962.
11.37 I M Swatman, *Development of the Ford 704 Gas Turbine Engine*, SAE Paper 291 A, Soc. Automotive Engineers, New York, 1961.
11.38 D A Noake, 'A New Concept in Land Vehicle Propulsion', *Armor*, Vol.76, No.3, May-June 1967, p.29.
11.39 G Engel and W S Anderson, 'Compactness of Ground Turbine Depends on Integral Recuperator', *Automotive Engineering*, Vol.79. No.8, August 1971, pp.13-17.
11.40 R M Ogorkiewicz, 'Gas Turbines or Diesels for Tanks?', *International Defense Review*, Vol.11, No.6, 1978, p.913-916.
11.41 J L Mason, 'Why Gas Turbines for Tanks?', *International Defense Review*, Vol.12, No.9, 1979, p.1537.
11.42 A D Baxter, Aero-Engines: Past, Present and Future, Proc.Inst.Mech.Engrs., Vol.171, No.1, 1957, p.88.
11.43 T Matsumura, Development of a Turbocharged Two-Cycle Air Cooled Diesel Engine, SAE Paper 720783, Soc. Automotive Engineers, New York, 1972.
11.44 R J Hooker, 'Orion – Gas Generator Turbocompound Engine', SAE Journal, Vol.65, May 1957, pp.51-56.
11.45 C Jones, The Curtiss-Wright Rotating Combustion Engine Today, *SAE Trans.*, Vol.73, 1965, pp.127-147.
11.46 C Jones and H Lamping, Curtiss-Wright's Development Status of the Stratified Charge Rotating Combustion Engine, *SAE Trans.*, Vol.80, 1971, pp.1956-1980.
11.47 F Feller, The 2-Stage Rotary Engine – A New Concept in Diesel Power, Proc.Inst. Mech. Engrs., Vol.185, 13/71, 1970-71.
11.48 C Jones, Rotary Engine Aims to SCORE Goals This Decade, *Chartered Mechanical Engineer*, Vol.34, No.4, April 1987, pp.46-50.

Chapter 12

Tank Transmissions

12.1 Propulsion Gears

The tractive effort and therefore the sprocket torque required to propel tanks varies from a high value at low speeds, which is needed for accelerating them rapidly or for ascending steep gradients, to the considerably lower value needed for travelling at maximum speed on level ground. The ratio of the two is of the order of 14 to 1, the maximum value of the tractive effort available for accelerating or hill climbing being determined for a vehicle of a given weight by the coefficient of traction and the value needed at maximum speed on level ground being determined, in essence, by the coefficient of rolling resistance. Such a variation in torque can not be provided by tank engines without the aid of a transmission system capable of changing the speed reduction ratio between the engine and the sprockets and, therefore, varying the ratio of the sprocket to engine torques. In addition, transmissions must be capable of taking up the drive to move tanks from rest and of reversing the direction of the drive, for driving them in reverse.

In the great majority of cases the required variation in the reduction ratio has been provided, as with other vehicles, by multi-speed gearboxes. The spread in the ratio between gears can be up to about 2:1 but 1.8:1 is a more acceptable maximum. If this were used and the gear ratios were in geometric progression the number of gears n necessary to span the torque ratio of 14:1 would be given by $1.8^{n-1} = 14$ and would equal 5.49, which in practice would imply a six-speed gearbox.

The use of a lower ratio of 1.4:1, which is common in automotive practice, would result in a smaller drop in power when changing gears and not only in smoother gear changes but also in the average power over the speed range being closer to the maximum, making the tank more agile. However, a spread in the gear ratios of 1.4:1 would also increase the number of gears to nine, making the gearbox more complicated and resulting in undesirably frequent gear changing. In practice a compromise solution is usually adopted, which amounts to departing from geometrical progression and using a larger spread, of up to 2:1, between the higher gears. This keeps down the number of gears to a reasonable level without undue loss of performance.

The choice of the number of gears depends to some extent on the way the torque of the engine varies with its speed. Thus, when engine torque is at its maximum at high speeds and decreases rapidly as the speed decreases, as it does with some highly turbocharged engines, more gears are called for than when the torque varies little over a wide range of engine speeds.

The actual design of tank gearboxes has followed, in principle, that of gearboxes developed for other types of vehicles. Thus, for the first twenty five years, or so, the gearboxes of tanks have been of the layshaft type, like those of contemporary cars and trucks. Gearboxes of this kind continued to be fitted in Soviet tanks in the 1970s, or even later. But in 1932, following their adoption for Armstrong Siddeley and Daimler cars, Wilson epicyclic gearboxes began to be tried in British tanks, starting with the A.6 E.3 Sixteen-Tonner and the A.7 E.2 experimental medium tank (12.1). A five-speed Wilson epicyclic gearbox was then adopted for the Mark II and Mark III light tanks built between 1930 and 1936. No other British tank was subsequently produced with epicyclic propulsion gears until the Chieftain battle tank of the 1960s, although Wilson epicyclic gearboxes with fluid couplings instead of clutches were used in several British wheeled armoured vehicles, from the Daimler scout car first built in 1938 to the Alvis Saladin armoured car last built in 1972. However, a Praga-Wilson five speed epicyclic gearbox was adopted in Czechoslovakia for the TNH tank first built in 1935 for Iran and later developed into the Pz.Kpfw.38(t), which was used in considerable numbers by the German Army during the Second World War.

The Wilson gearboxes made it much easier for drivers of tanks to change gears than the earlier crash-type layshaft gearboxes and they incorporated a mechanism for preselecting gears. During the Second World War a further advance took place with the adoption in 1942 of the General Motors Hydramatic transmission for the US M5 light tank. The Hydramatic transmission was originally produced in 1939 for passenger cars and like the Wilson gearboxes used epicyclic or planetary gear trains as well as a fluid coupling instead of a friction clutch. But the Hydramatic transmission represented an advance on the Wilson epicyclic gearboxes in performing gear changes automatically, through a hydraulic pressure control system (12.2).

After its successful introduction in the M5 light tank, the Hydramatic transmission was used in other US vehicles from the M24 light tank to the M59 armoured personnel carrier produced during the 1950s. Experience gained with it paved the way for the development of other automatic transmissions with epicyclic gear trains but with hydrokinetic torque converters instead of fluid couplings.

12.2 Transmissions with Hydrokinetic Torque Converters

Hydrokinetic torque converters were originally devised by H Fottinger in Germany where the first was made in 1908. To begin with they were used mainly for marine drives of very high power but in the 1920s they began to be developed for automotive vehicles and one designed in Sweden by A Lysholm was adopted in 1931 in Britain by Leyland Motors Ltd for some of their buses as the Lysholm-Smith torque converter (12.3).

This was followed in 1937 by the introduction in the United States of General Motors buses with Lysholm-Smith torque converters and four years later by their use in US tanks. In the meantime, in 1934, the Steyr-Daimler-Puch Company began to produce in Austria the eight-wheeled Austro-Daimler ADGZ armoured car with a Voith Turbo-Getriebe, a torque converter developed in Germany. In 1940 the Landsverk Company also started to build in Sweden the Strv m/40 light tank with a Lysholm-Smith torque converter. However, the use of torque converters in tanks did not become established until they began to be used in US tanks. The first of them was the T1E2, later M6, heavy tank built in 1941. It was not put into service but its example was followed by the use of torque converters in a series

of experimental medium tanks, which started with the T20 of 1943 and led to the M26 Pershing of 1945, and also in the M18 tank destroyer built in 1943 and 1944.

The torque converters used in the M26 tank and the M18 tank destroyer were part of the General Motors Torqmatic transmission and were once again of the Lysholm-Smith type. Like the other Lysholm-Smith torque converters, they had a three-stage turbine and their output torque varied continuously with the output speed from a maximum of 4.8 times the input torque when the turbine was stalled to zero at an output-to-input speed ratio of about 0.9. This made them very attractive from the point of view of accelerating tanks rapidly and smoothly from rest, and without any gear changing. However, they were also relatively inefficient, their efficiency reaching a maximum of 85 per cent in the middle of their speed range but falling rapidly to zero at high and low speeds. Therefore, to keep them operating within the range of speeds in which they were relatively efficient, they needed to be connected in series with a number of gears. This was done in the Torqmatic transmission which provided three forward speeds as well as reverse by means of epicyclic gear trains similar to those of the Hydramatic transmission but without the automatic gear change system of the latter.

Another approach to overcoming the inefficiency of the Lysholm-Smith torque converters was embodied in their installation in the Swedish Strv m/40 tank as well as the Leyland and General Motors buses. This took the form of a double-acting clutch which disengaged the torque converter and provided direct drive at higher vehicle speeds. But this was not done in the Torqmatic transmission and because the drive was taken in it through the torque converter at all times the fuel consumption of tanks fitted with it was high.

Nevertheless, the use of the torque converters in the M26 tank and M18 tank destroyer was considered highly successful and they were incorporated subsequently in all US tank transmissions. In particular, a torque converter was incorporated in the CD-850 transmission developed by the Allison Division of General Motors in the mid-1940s and first produced in 1949 for the M46 medium tank.

Like the Torqmatic, the original version of the CD-850 had a single-phase torque converter but the CD-850-2 had a polyphase torque converter with two rows of stator blades mounted on free-wheels, instead of being fixed as in the Lysholm-Smith converters, so that they were free to rotate in the same direction as the turbine but were locked against rotation in the opposite direction. As a result, when the output-to-input torque ratio reached unity the stators ceased to act as reaction members and began to rotate with the turbine, which made the converter act as a fluid coupling. From this point on the output torque remained equal to the input torque but the efficiency increased linearly with output speed, as it does in fluid couplings, instead of falling off rapidly as it does with single-phase torque converters.

The use of such polyphase torque converters was foreshadowed by the Trilok converter-coupling developed in Germany and installed in the B.IV radio-controlled demolition charge laying vehicle which was produced in 1942-1943. The use of a converter-coupling in the Allison CD-850-2 transmission was also in keeping with the contemporary US automotive practice, exemplified most clearly by the Dynaflow transmission of Buick cars (12.4). The result of it was a significant improvement in the overall efficiency by comparison with the earlier torque converter transmissions. The converter-coupling of the CD-850 transmissions still gave a torque multiplication of 4.3:1 but, in keeping with the general trend to lower

ratios, this was reduced to 3.6:1 in later versions of it.

Given the improved performance of the converter-coupling, only two forward, as well as one reverse, gears were considered necessary for the CD-850. But, although they extended the range of operation, its efficiency left room for further improvement, which was soon made with the introduction of the CD-500 transmission developed for the M41 light tank. Nevertheless, the CD-850 was not only produced in large numbers, for the M47, M48 and M60 tanks, but it continued to be fitted and retrofitted in tanks well into the 1980s.

The torque converter of the CD-500 was similar to that of the CD-850 in being of the polyphase, single-stage type with four elements, that is with a pump, a single-stage turbine and two stators on free-wheels. But, in addition, it incorporated a lock-up clutch which locked the pump and the turbine of the converter together at higher vehicle speeds, causing the drive to be transmitted mechanically and thereby eliminating the losses associated with fluid drives.

The torque converter of the CD-500 still had a relatively high torque ratio of 3.8:1 at stall and was combined with only two forward gears but as a converter-coupling with a lock-up clutch it set a pattern which has been followed in tank transmissions ever since it was introduced in the M41 light tank in 1950.

Although they represent alternative approaches to improving the overall efficiency of transmissions with torque converters, the adoption of lock-up clutches did not eliminate the mounting of stators on free-wheels. The reasons for it are that the continued use of free-wheels helped to make the transition from the torque converter mode of operation to direct drive, with the converter locked-up, more gradual and also reduced energy losses due to the churning of the fluid in the converter when it was locked up, compared with stators which were fixed at all times.

The torque converters of the Allison XT-1400 transmission, which should have replaced the CD-850 in the M48 tanks in the mid-1950s but which was only installed in the M51 and M88 armoured recovery vehicles, have still had two stators (12.5). But the torque converters of more recent Allison transmissions, such as the XTG-411-2A of the M107, M109 and M110 self-propelled guns and the X-1100 of the M1 tank have a single, free-wheel-mounted stator. This is also the case with the ZF 4HP250 transmission of the Leopard 1, the ZF LSG 3000 of the South Korean Type 88 and the Engesa Osorio, the David Brown TN 37 and TN 54 transmissions of the Challenger and the ESM 500 of the AMX Leclerc.

Thus, almost all the more recently adopted torque converters have been of the simpler, three-element, single-stage, two-phase type. The only exception to this have been the SRM torque converters of the Renk transmissions and in particular of the HSWL 354 of Leopard 2, which also have a single stator but which have two, instead of one, turbine stages.

Otherwise there has been a general trend to lower torque ratios at stall than those originally adopted, the ratios ranging from 3.5:1 in the TN 37 to 1.9:1 in the X-1100. There has also been a trend to use torque converters mainly for moving vehicles off from rest. However, even then torque converters with, typically, a torque ratio at stall of about 2.5:1 make it possible to reduce considerably the number of gears which a transmission needs to span the range of tanks' torque requirements. The actual number of forward gears generally used with torque converters since the late 1950s has been four but in some recently developed transmissions there are more gears, mainly to compensate for the less flexible characteristics of high output diesel engines. Thus, the four-speed TN 37 has been followed by the six-speed TN 54 and the ESM 500 has been developed from its

original, four-speed version into one with six forward speeds.

By the 1980s the use of torque converters had proved so successful that it had become almost universal in tanks of other than Soviet design. But it has been claimed that they may become redundant when gas turbines are used, because the output torque of the latter also rises as the speed of their free power turbines decreases. In fact, at stall the torque of a typical power turbine is twice the torque at the rated speed and power. As it happens, the X-1100 transmission used with the AGT-1500 gas turbine of the US M1 tank incorporates a torque converter but the Garrett GT-601 gas turbine has been used without one. If the torque converter could be dispensed with, this would obviously save space, eliminate the power losses due to it and reduce drastically transmission oil cooling requirements. However, eliminating it could also cause overheating of the heat exchanger whenever the power turbine was operated stalled for any length of time.

There has also been some interest in the possible alternatives to the epicyclic gearboxes which have proved so successful when used in combination with torque converters. The reason for their success is that they lend themselves to automatic, or semi-automatic, changing of gears by means of hydraulically operated clutches or brakes which go with epicyclic gear trains. In consequence they have made tanks easier to drive. They also make it possible to change gears without interrupting the drive, which is particularly valuable when moving off the roads. Such 'hot-shift' transitions from one gear ratio to the next are achieved by the simultaneous operation of the clutches or brakes controlling them.

However, the clutches and brakes of epicyclic gearboxes make them bulky and drag between their elements gives rise to significant power losses. In consequence,

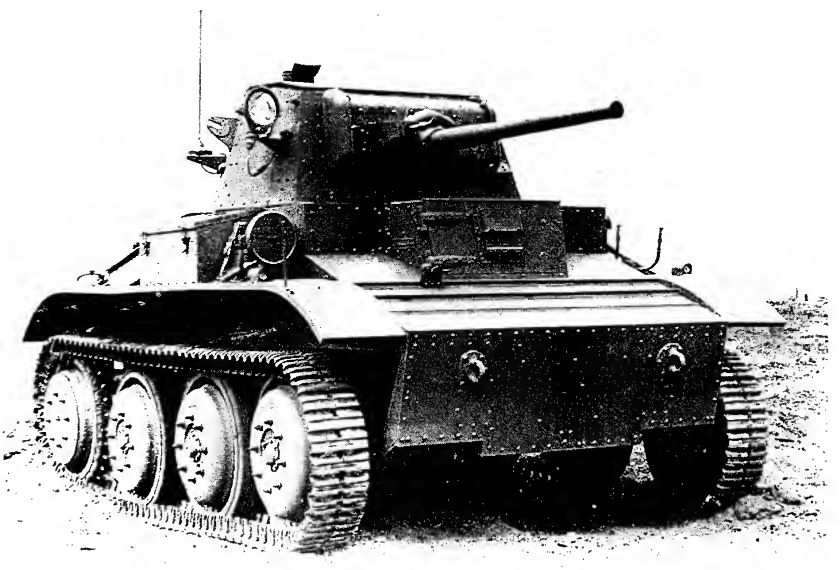


Fig. 12.1 Tetrarch light tank which incorporated a curved track steering system. (Vickers-Armstrongs).

there has been some interest again in layshaft gearboxes and in particular in gearboxes with two layshafts engaged by separate clutches, each shaft carrying alternate gears. In contrast to the earlier, single layshaft gearboxes, those with twin layshafts make it possible to hot-shift. At the same time, they contain fewer power dissipating elements than the epicyclic gearboxes, so that their efficiency has been estimated at 93 to 95 per cent, compared with about 85 for a typical epicyclic gearbox. But whether they will prove to be significantly more efficient and less bulky than epicyclic gearboxes is open to question.

12.3 Steering of Tracked Vehicles

Steering of tracked vehicles is a problem peculiar to them to which the almost universal solution has been the use of skid steering. This amounts to turning a vehicle by creating a difference between the speed of one of its tracks in relation to the other.

However, there are at least two other ways of steering tracked vehicles which have been tried from time to time. One of them is curved track steering. This involves bowing the tracks in the horizontal plane by pivoting some or all of the road wheels about vertical axes or by displacing them sideways relative to each other. Curved track steering was proposed as early as 1912 by L E de Mole, although his ideas were not put into effect (12.6). However, another form of curved track steering was adopted by P Johnson for the Light Infantry Tank designed in Britain in 1921. It involved the use of laterally flexible 'snake tracks' with lubricated spherical joints between the track plates but these proved troublesome and the concept of curved track steering was abandoned (12.7).

The only significant and relatively successful use of curved track steering did not come until 1936, when it was embodied in the Tetrarch light tank designed at Vickers-Armstrongs under the direction of L F Little. The Tetrarch and its derivatives, the Harry Hopkins light tank and the Alecto self-propelled gun, incorporated

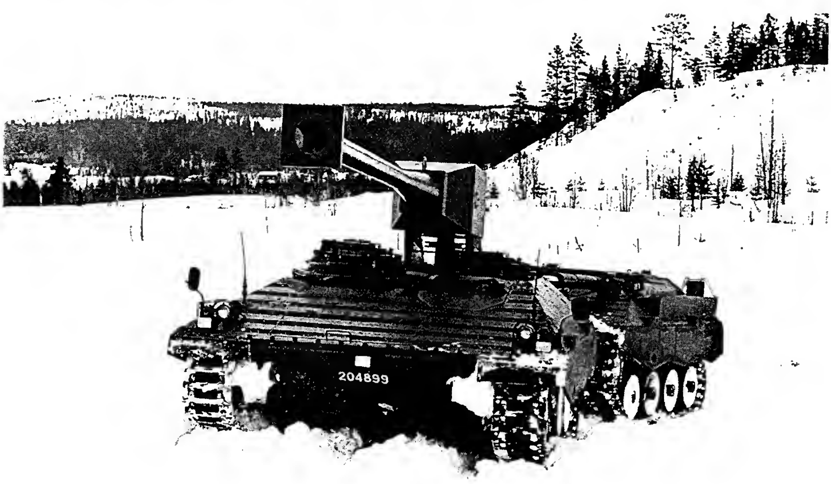


Fig. 12.2 Swedish UDES-XX-20 articulated vehicle steering with its two units at an angle to each other in yaw. (Swedish Army)

a complete system of track setting by pivoting all four road wheels on each side and they could perform large radius turns by track curving alone. This was accomplished with a conventional, all-steel type of track, laterally flexible only to the extent permitted by the clearances between the track pins and the holes in the track links. The use of curved track steering produced a significant improvement in the overall efficiency of the Tetrarch and its derivatives due to the elimination of much of the power losses associated with skid steering (12.8). However, skid steering still had to be used for tight turns and the track setting mechanism made the vehicles more complicated.

The second alternative to skid steering has been provided by articulated vehicles consisting of two units which can be turned relative to each other in the horizontal plane. The first articulated tracked vehicle, which was a lorry, was built in Britain in 1913 by B J Diplock (12.9). Articulated construction was then briefly considered in 1915, during the course of the studies and experiments which led to the construction of the first British tanks (12.10). But nothing came of it and little further interest was shown in articulated tracked vehicles until the 1950s, when a number of special-purpose, unarmoured, articulated cargo carriers were built in the United States and Canada, and subsequently in Sweden (12.11). They demonstrated the superior performance of this type of vehicle over snow and muskeg or peat bogs but, although a number of design studies of articulated armoured vehicles were carried out in the United States during the late 1950s, they were not considered superior, overall, to more conventional tracked armoured vehicles and none were built until 1981. This first articulated tracked armoured vehicle was the UDES-XX-20 tank destroyer prototype built by the Hägglunds company under contract from the Swedish Army. But although it proved mechanically successful, the development of the UDES-XX-20 was abandoned in 1984.

12.4 Mechanics of Skid Steering

The basic features of skid steering can be established by considering a vehicle with laterally rigid tracks which executes a turn by following a circular path of radius R and with centre at O, as shown in Fig.12.3. Assuming that the tracks slip, which is equivalent to them rotating relative to the ground about instantaneous centres O_i and O_o located at distances a_i and a_o from the centre lines of the respective tracks, it can be shown from the kinematics of the vehicle that (12.12):

$$R = \frac{\frac{C}{2}(V_o + V_i) + (a_o V_i - a_i V_o)}{V_o - V_i} \qquad \text{........................ 12.1}$$

where V_o = velocity of outer track
V_i = velocity of inner track
C = distance between centre lines of tracks

In the simplest case, when longitudinal resistance and centrifugal forces are neglected, $a_o = -a_i = a$ and equation 12.1 becomes:

$$R = \frac{V_o + V_i}{V_o - V_i}\,\frac{(C + \beta L)}{2} \qquad \text{.................................. 12.2}$$

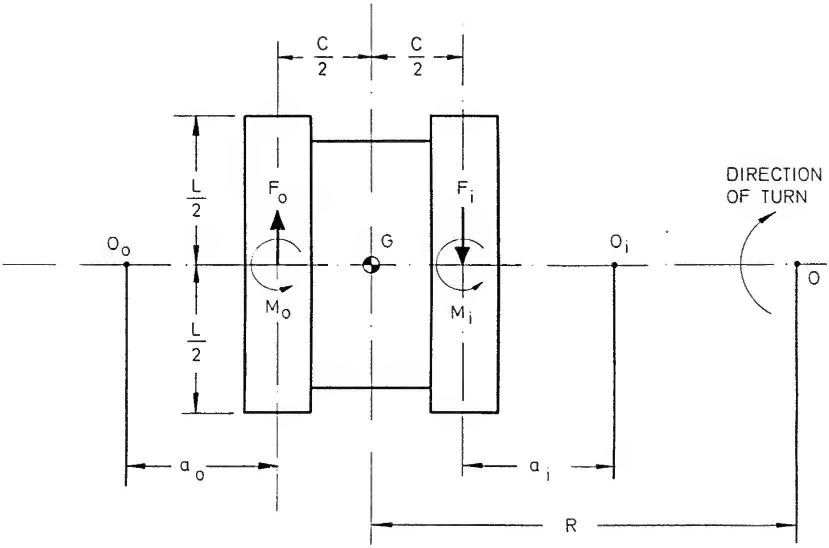


Fig. 12.3 Mechanics of tracked vehicle steering.

where L = length of track on the ground and $\beta = 2\,a/L$, or zero in the absence of slip. If the forward speed of the vehicle V_m is the arithmetic mean of V_o and V_i, then equation 12.2 leads to the following expressions:

$$V_o = V_m\left(1 + \frac{C+\beta L}{2}\right) \qquad \text{12.3}$$

and $$V_i = V_m\left(1 - \frac{C+\beta L}{2}\right) \qquad \text{12.4}$$

Thus, for a vehicle with known values of L and C the radius of turn can be calculated from equation 12.2 given the values of track velocities, or the latter can be calculated from equations 12.3 and 12.4 given the radius of turn and the vehicle speed, provided that in either case the value of β can be found. To derive an equation from which this can be found it is necessary to consider first the equilibrium of forces acting on one of the tracks of the vehicle, assuming that one half of the vehicle weight is uniformly distributed over its length and that the friction between it and the ground is isotropic. If the track happens to be the outer one it can be shown that (12.13):

$$F_o = \mu\frac{W}{2}\beta\sinh^{-1}\frac{1}{\beta} \qquad \text{12.5}$$

which is frequently written as,

$$F_o = \mu\frac{W}{2}k \qquad \text{12.6}$$

where F_o = longitudinal force on outer track
W = vehicle weight
μ = coefficient of friction between track and ground
k = $\beta \sinh^{-1} \frac{1}{\beta}$

Then, considering the equilibrium of moments acting on the vehicle and assuming, as before, no longitudinal resistance to motion and therefore no resultant tractive force, isotropic friction, constant radius and speed of turn, and neglecting centrifugal forces, it can be shown by taking moments about G and making use of equation 12.5 that (12.14, 12.15):

$$\frac{C}{L} = \frac{\sqrt{1+\beta^2}}{2\beta \sinh^{-1}\frac{1}{\beta}} - \frac{\beta}{2} \qquad \ldots\ldots 12.7$$

Equation 12.7 relates β, and consequently k, to the geometry of the vehicle, which is characterised by the L:C ratio. The relationship between β, as well as k, and L:C is shown graphically in Fig.12.4 and values of β read off it make it

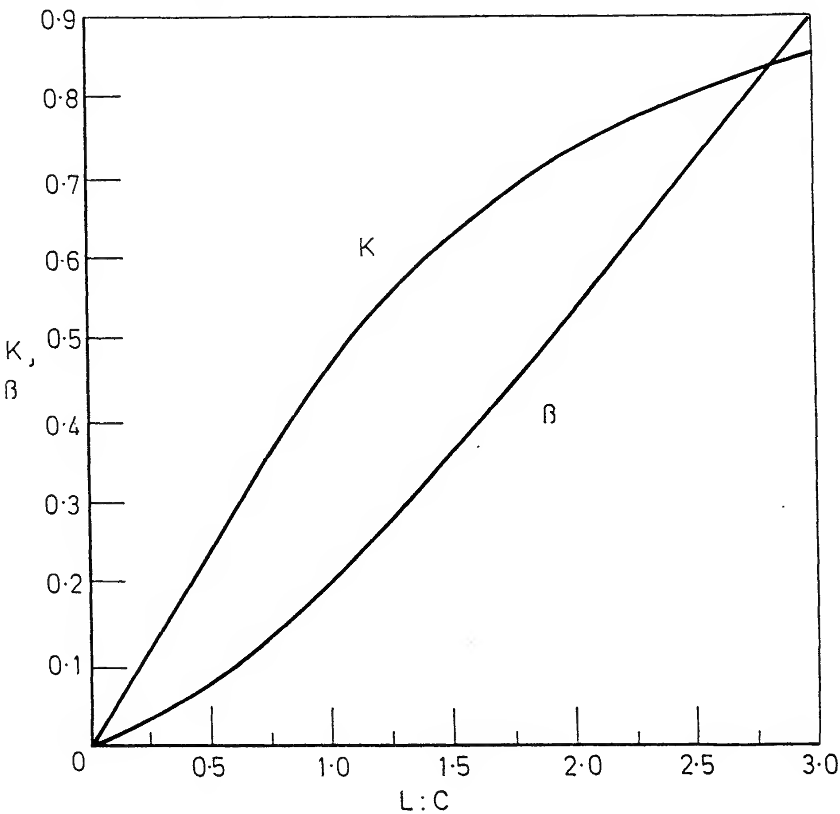


Fig. 12.4 Curves of β and k versus L:C.

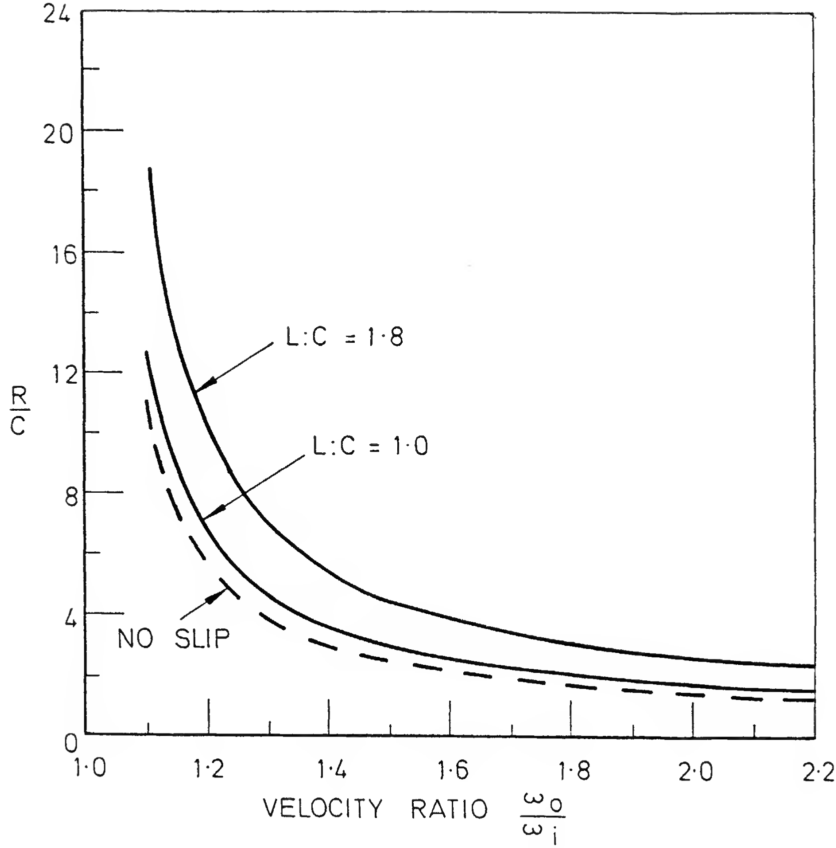


Fig. 12.5 Ratio R:C plotted against the ratio of track sprocket angular velocities for a range of values of L:C.

possible to calculate the radius of turn for any particular ratio of L to C and of tracks speeds V_o and V_i, or track sprocket angular velocities ω_o and ω_1. Results which cover the range of practicable values of L:C are shown in Fig.12.5, where the radius of turn, normalised by being divided by the distance between the track centres C, has been plotted against ω_o/ω_i

Given values of β and k, and making use of equations 12.3, 12.4 and 12.6, it is also possible to calculate the power P_o and P_i absorbed in skidding the outer and inner tracks, respectively, for any given vehicle speed and turning radius, because:

$$P_o = F_o\, V_o = \frac{\mu W k}{2}\, V_m \left(1 + \frac{C + \beta L}{2\,R}\right) \qquad \text{12.8}$$

$$\text{and } P_i = - F_i V_i = - \frac{\mu W k}{2} V_m \left(1 - \frac{C + \beta L}{2 R}\right) \qquad \ldots\ldots\ldots\ldots\ldots \; 12.9$$

Substitution of typical values in equations 12.8 and 12.9 shows that the amount of power involved in skidding tracks is considerable and can greatly exceed the power developed by the vehicle's engine. However, the power at the inner track is negative because it experiences a retarding force while it continues to move forward. This means that the inner track receives power from the ground and if that power can be transferred to the outer track it can offset much of the power required to skid the latter. There is, therefore, a very strong case for the use of steering systems which can transfer power from the inner to the outer track or, in other words, which are regenerative. Otherwise skid steering results in rapid deceleration of vehicles and in the need to absorb the power generated by the inner track in brakes which gives rise to heat dissipation problems as well as being wasteful.

Equations 12.8 and 12.9 have been derived, of course, on the basis of greatly simplifying assumptions. Nevertheless, they provide a good indication of the magnitude of the problem of skid steering. More accurate results, which take into account resistance to motion, anisotropy of friction and centrifugal forces, can be obtained by numerical analysis (12.16). Alternatively, more accurate results can be obtained by modifying, on the basis of experiments, equation 12.6, which implies that the turning forces at a given speed are independent of the turning radius. In fact, these forces decrease with the radius of turn and this can be taken into account by replacing k in equation 12.6 by an experimentally determined variable k_v, which depends on R.

The variation of the ratio k_v:k with R is shown in Fig. 12.6, the curve representing it being based on results obtained with the US T48, M51 and M109 vehicles (12.17). Very similar results have been obtained with the British Scorpion light tank but somewhat higher values of the k_v:k ratio have been quoted for the Chieftain tank (12.18).

12.5 Types of Steering Mechanisms

The difference between the speeds of the tracks of a vehicle which is required to skid-steer it can be created in a number of different ways. About the most direct and simplest of them is provided by the clutch-and-brake steering system shown diagramatically in Fig. 12.7. Steering is effected with it by disengaging the clutch on the side of what is to be the inner track, which disconnects the drive to it, and then by applying the corresponding brake to slow down the undriven inner track still further. When the brake stops slipping the vehicle executes a skid turn about the locked track.

Clutch-and-brake steering allows all engine power to be transmitted to the outer track but does not provide for the transfer to it of any of the power generated at the inner track. It is not, therefore, regenerative and requires a considerable amount of power to be dissipated at the inner track while it is slipping. The reduction in the speed of the inner track which clutch-and-brake steering causes without a corresponding increase in the speed of the outer tracks results in a slowing down of the vehicle but the consequent change in its momentum helps to initiate a turn and makes the vehicle change direction more rapidly. On the other hand, clutch-and-brake steering is discontinuous, since the initiation of a turn involves the disengagement of the drive to one of the tracks followed by the engagement of another

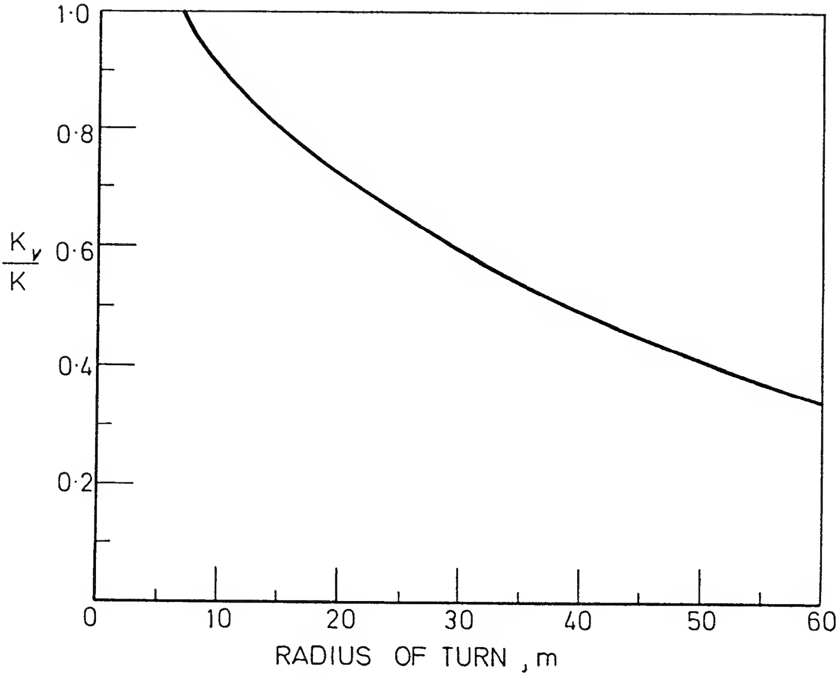


Fig. 12.6 Ratio k_V/k versus radius of turn R.

form of track control. This implies the risk of reversed steering, that is of turning in the opposite sense to that expected by the driver, whenever steering is attempted while the vehicle happens to be overrunning the engine, as it might do when going downhill. Under such conditions the track which has been declutched and not braked can run more freely than the driven track, with the result that the vehicle turns towards the side of the latter instead of away from it. The risk of reversed steering can be largely eliminated by arranging the disengagement of the clutches and the application of the brakes to overlap but this requires careful adjustment of the controls and may result in energy losses due to the drag of the control members.

In many cases clutch-and-brake steering systems have not actually embodied clutches but have made use of epicyclic gear trains to perform their function. In particular, epicyclic final drive reduction gears have been used instead of clutches to disengage the drive to the tracks by releasing their reaction member, this being followed by the application of a track brake, as before. An example of such an epicyclic clutch-and-brake system is shown diagramatically in Fig. 12.8.

The clutch-and-brake steering system can be improved upon if, instead of disconnecting the drive to one of the tracks and then trying to bring it to rest, one track is merely driven at a lower speed than the other. This can be accomplished by having a two-speed set of gears in the drive to each track and changing down on one side or the other. An example of a geared steering system which provides for this is shown in Fig. 12.9. Once the driving brake has been released and the steering

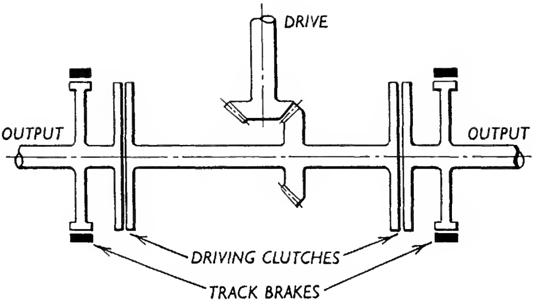


Fig. 12.7 Clutch-and-brake steering system.

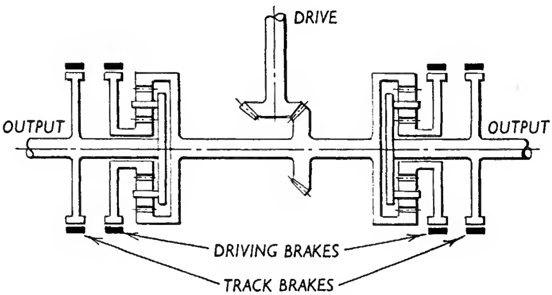


Fig. 12.8 Epicyclic clutch-and-brake system.

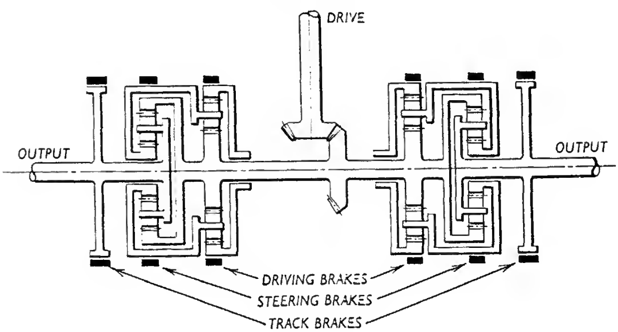


Fig. 12.9 Geared steering system.

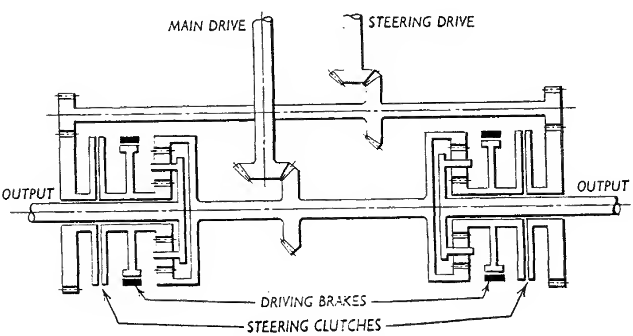


Fig. 12.10 Multi-geared steering system of the Panther tank.

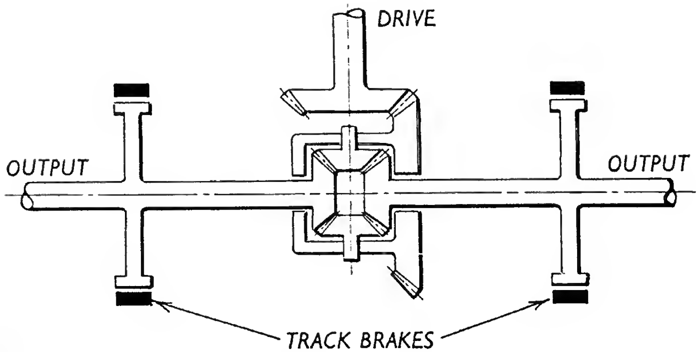


Fig. 12.11 Braked differential.

brake has stopped slipping in such a system it becomes fully regenerative, the power generated during a turn by the inner track being transferred, through the gears, to the outer track.

Driving the tracks at different speeds also provides larger radius turns than those possible with clutch-and-brake systems, except by the inefficient process of brake slipping. In other respects the characteristics of a geared system are similar to those of the clutch-and-brake system. Thus, like the latter, it is discontinuous, provides a positive drive to both tracks during straight ahead running and gives a lower mean track speed during a turn. Apart from being somewhat more elaborate, it suffers from only one disadvantage in relation to the clutch-and-brake system which is that it can not provide turns as tight as the skid turns about the locked track obtainable with the latter. In consequence, the geared system has been used, in almost all cases, in combination with the clutch-and-brake system, the outcome being a two-stage steering system of which that illustrated in Fig.12.9 is an example.

An obvious refinement of geared steering is the use in the drive to each track of a gearbox with more than two speeds, which provides more than one radius of turn. Epicyclic gearboxes with up to eight speeds in the drive to each track have been tried in fact but this proved to be a cumbersome arrangement and has not been adopted.

Instead a much more elegant form of multi-geared steering has been devised, which is shown diagramatically in Fig.12.10. It consists of an epicyclic train at each output shaft with the annuli of the epicyclics driven from the output of the propulsion gearbox and with the sun gears fixed for straight running by the brakes. To steer the driving brake on one side is released and the clutch on that side is engaged, so that the corresponding sun is driven in the opposite sense to the annulus and the speed of the output shaft is reduced. Since the drive to the suns comes from the input of the propulsion gearbox there are as many minimum radii of turn as there are speeds in the gearbox. In addition, when the driving brake is kept released and the clutch is disengaged, a skid turn about a track can be obtained as a follow-on to the geared turn. Moreover, when the propulsion gearbox is in neutral and one of the steering clutches is engaged the output shafts are driven in opposite sense, so that one track moves forward and the other backwards giving a pivot turn. Apart from being simpler, this type of multi-geared steering

system also has the advantage over that with an epicyclic gearbox in the drive to each track of a much shorter path, not involving the propulsion gears, for the transfer of the power generated by the inner track to the outer track.

Other steering systems have been based on differential mechanisms, which differ from the clutch-and-brake and geared steering systems in transmitting the drive continuously to both tracks.

The simplest and earliest form of a differential steering system consists of a simple differential interposed in the drive to the tracks and of an independently operated brake at each of the half-shafts, as shown in Fig.12.11. Steering is effected by applying one of the brakes, which slows down the track on its side and simultaneously speeds up the track on the other side. The braked differential system is evidently very simple but it is also very inefficient. This is due not only to the fact that it does not transmit the power generated by the inner track during a turn to the outer track but also to a large proportion of the engine power being dissipated in the steering brake. In other words, the braked differential system is non-regenerative and engine as well as inner track power are wasted in the steering brake while it is slipping. When the brake is locked all the engine power is transmitted, of course, to the outer track but turns under these conditions are only practicable at very low vehicle speeds.

The major disadvantages of the braked differential are avoided by the controlled or geared differential. In this no attempt is made to bring the inner output shaft to rest by the application of a brake but only to a fraction of the mean speed of the two shafts by adding supplementary gears to a simple differential, as shown in Fig.12.12. In a mechanism of this kind no engine power is wasted in the steering brakes and, what is more, power generated during a turn by the inner track is transferred to the outer track, which helps to supply the power required by that track and makes the system regenerative.

However, the controlled differential also has a number of shortcomings. One arises from the fact that when the brakes are off it acts as a simple differential, giving a balance between the input and output torques but not fixing their ratio, which is governed by the reactions between the tracks and the ground. In consequence, it depends on these reactions being equal for the vehicle to move straight and when they vary it produces undesirable effects, such as drifting on cambered roads or veering during deceleration. In the extreme, when one track loses traction and spins on muddy ground, or when obstacles are negotiated at an angle, differential action leads to a loss of drive to the other track and stalling of the vehicle.

Another major shortcoming of the controlled differential is that its gearing gives only one minimum radius of turn, which has to be a compromise between the requirements for large radius turns at high speed and tight turns at low speeds. Large radius turns can, of course, always be made by slipping the brake but this is inefficient and manoeuvrability in confined spaces can only be improved by fitting an additional set of brakes – one to each output shaft. When one of these brakes is applied instead of the normal steering brake the controlled differential behaves like a braked differential. Thus, when the brake stops slipping, a skid turn is obtained about the locked track.

A considerable further improvement on the braked differential is provided by the double differential which, in its original form, consists of two simple differentials arranged in parallel with their output shafts geared together, as shown in Fig.12.13. The two differentials can both be driven from the output of the propulsion gearbox, in which case the system behaves in exactly the same way as the controlled differential. But if one of them is driven, instead, from the input of the

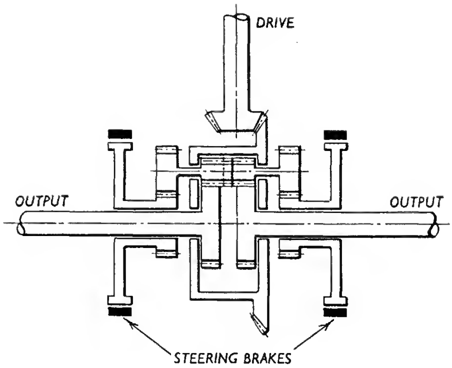


Fig. 12.12 Controlled, or geared, differential.

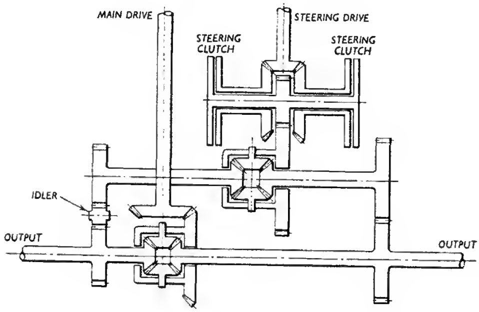


Fig. 12.13 Double differential steering system.

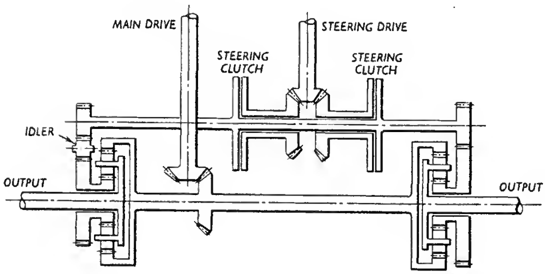


Fig. 12.14 Epicyclic equivalent of the double differential system shown in Fig.12.13.

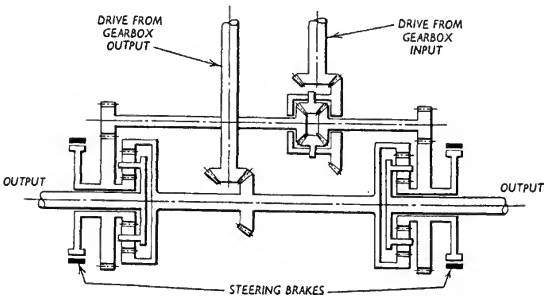


Fig. 12.15 Triple differential steering system.

propulsion gearbox then the system gives a different minimum radius of turn for each gear in the gearbox, the lower the gear the smaller being the radius, which is generally required. Moreover, when the propulsion gearbox is in neutral and the steering drive is engaged by one of the steering clutches it provides a pivot turn, with one track going forwards and the other backwards, giving exceptional manoeuvrability in confined spaces.

Like the controlled differential, the double differential system is regenerative and increases the speed of the outer track when the inner one is being slowed down, so that the speed of the vehicle fitted with it does not decrease during a turn, as it does when geared steering is used. But, instead of the single radius of turn of the controlled differential, it can provide as many radii as there are propulsion gears and makes it possible to eliminate differential action between the tracks when it is not wanted.

The advantages of double differential steering systems have led to their extensive use in tanks but their original form based on bevel differentials has been superseded by kinematically equivalent arrangements of epicyclic gears, the simplest of which is illustrated in Fig.12.14. The system shown is based, like the others, on two epicyclic gear trains working in parallel, one at each output shaft. The annuli of the epicyclics are driven from the output of the propulsion gear set and, when the steering drive is engaged by one of the steering clutches, their suns are driven in the opposite senses, which slows down one output shaft and speeds up the other to give a turn in the required direction. If the propulsion gears are in neutral the output shafts turn in opposite directions which gives a pivot turn. When the steering clutches are disengaged the cross shaft connecting the sun gears balances the torques acting on them, which results in a balance of output shaft torques, as with a conventional differential. However, the undesirable differential action between the output shafts can be prevented easily by locking the cross shaft.

Double differential steering becomes even better when the mechanical steering drive is replaced by a hydrostatic steering drive consisting of a variable displacement pump and a fixed displacement motor. The hydrostatic drive offers the advantage of infinitely variable control over the radius of turn, from infinity to its minimum value imposed by the propulsion gear in which the transmission is operating. The hydrostatic drive also fixes the ratio of the speeds of the output shafts at whatever setting it is operating so that steering is achieved by velocity control and is not affected by changes in the forces acting on the tracks, as it is with simple double differential systems. One particular aspect of it is that in the straight ahead mode of motion the motor of the hydrostatic drive is prevented from rotating by locked-in fluid, which effectively applies a brake to the steering cross shaft and automatically eliminates differential action between the tracks when it is unwanted. Another advantage of hydrostatic control is that it produces a true pivot turn when the propulsion gears are in neutral, with the tracks moving at equal and opposite speeds, whereas a mechanical steering drive of a simple double differential system may or may not produce such a turn, as it depends for it on the reactions from the ground.

Development of differential steering mechanisms has also produced the triple differential system, shown diagrammatically in Fig.12.15. This is very similar functionally to the double differential system and has similar advantages. Thus, it is regenerative and, if the steering drive is taken from the input side of the propulsion gears, it gives radii of turn which decrease as the propulsion gears are shifted down and it also gives a neutral or pivot turn.

However, it differs from the double differential system in power being transmit-

ted by both of its input shafts not only when steering but also during straight ahead running. This makes it unsuitable for the application of a hydrostatic steering drive and, therefore, of infinitely variable steering control. It is also more difficult with it to eliminate differential action between the tracks and its attendant disadvantages when driving straight ahead or when crossing obstacles.

The triple differential system is not actually a unique mechanism but exists in two somewhat different forms. In one, which is illustrated in Fig.12.15, the sun gears of the epicyclic trains at the output shafts rotate in the same sense as the annuli. Consequently, in this system engine power is simply split between the main drive to the annuli and the steering drive to the suns and then recombined in the epicyclics. In the other system there are idlers between the gears on the ends of the steering differential half-shafts and the sun gear clusters, so that the suns rotate in the opposite sense to the annuli, while the torques on the suns and the annuli are in the same sense. This means that the powers transmitted by the suns and the annuli are of opposite sign and, therefore, that power is recirculated from the suns through the steering drive to the propulsion gears. The effect of it on the latter is to increase their speed rather than the torque acting on them and is not, therefore, as serious as might be thought. At the same time triple differential systems with recirculation of power require less speed reduction to be provided by the propulsion gears for a given overall speed reduction than the split power systems and this makes for smaller gearboxes.

12.6 Evolution of Steering Systems

Braked differential and clutch-and-brake steering, the two simplest methods of steering tracked vehicles, had been developed before the first tanks were conceived and were inevitably resorted to when tanks began to be built.

Braked differential steering was the subject of British Patent No.16,345 granted in 1904 and was incorporated in the first successful fully tracked tractor built in 1905 by Richard Hornsby and Sons. Ten years later it was also incorporated in Little Willie, the first of the British tanks, which continued to be provided with it up to the Mark IV of 1917. However, for sharp turns the differential fitted in them was locked out and they were steered by clutch-and-brake methods. Thereafter braked differential steering was used in some very light vehicles, notably in the Carden Loyd tankettes of the late 1920s and in their descendants, the Bren Gun Carriers, which were produced on a large scale during the Second World War. Since then braked differential steering has been virtually abandoned, because of its inefficiency.

Clutch-and-brake steering appears to have been conceived in the United States, at the Holt Company, as early as 1891 and was first successfully demonstrated in a Holt steam traction engine in 1904 (12.19). Following the example of the Holt tractors, clutch-and-brake steering was adopted in the first French tanks built by the Schneider Company. Clutch-and-brake methods were also used when steering the first British tanks of 1916 and 1917, as already mentioned, although in a somewhat less direct way. The differential installed in these tanks could be locked out and they were then steered by putting one of the auxiliary gearboxes incorporated in the drive to each track into neutral after which the track brake on the same side was applied (12.20).

Clutch-and-brake steering systems were subsequently used in most tanks built during the 1920s and 1930s. Typical examples of their use are provided by British light tanks, from the Vickers Carden Loyd Mark VIII of 1928 to the Light Tank

Mark VI of 1936, by the German Pz.Kpfw.I and the Soviet T-26. They were also used in heavier British tanks, from the Vickers Medium Mark I of 1922 and the A.1 Independent heavy tank to the early cruiser tanks up to the Mark IV of 1939 and the contemporary Matilda and Valentine infantry tanks. Clutch-and-brake steering was also used in all Soviet medium and heavy tanks, from the BT and the T-35 of the 1930s to the T-34-85 and KV tanks of the Second World War.

In heavy tanks and in particular in tanks as heavy as the 52 ton KV-2 clutch-and-brake steering systems proved unsatisfactory. But in lighter vehicles with high power-to-weight ratios and adequately large brakes they were reasonably satisfactory and they continued to be used in vehicles such as the Soviet PT-76 amphibious light tanks produced during the 1950s and the Swedish Ikv-91 tank destroyer built during the mid-1970s.

The epicyclic variant of clutch-and-brake steering was originally devised in Britain in 1916 by W G Wilson and was put into service in 1918 in the Mark V tank. After the First World War it fell into disuse but in the 1930s it reappeared in German Pz.Kpfw.III and IV medium tanks and in Italian tanks, from the L.3 tankette to the M 13/40 medium tank. However, at the end of the Second World War it suffered another eclipse.

The use of geared steering was proposed as early as 1917 in the form of Wilkins' Clutch Gear, which consisted of a three-speed and reverse gearbox installed in the drive to each track of a modified British Mark IV tank (12.21). In principle it was provided even earlier in British tanks which, up to the Mark IV, had a two-speed gearbox in the drive to each track but which in general appear to have been steered either by the braked differential or by the clutch-and-brake methods. In any event, the first successful geared steering system was designed in 1918 by W G Wilson for the Anglo-American Mark VIII heavy tank. This had a two-speed epicyclic gearbox in the drive to each track and was steered by changing down on one side to obtain a geared turn or, if a tighter turn were required, by releasing both epicyclic trains, thereby disengaging the drive, and applying the track brake to obtain a skid turn, as in any clutch-and-brake system. The gears on both sides were also shifted down simultaneously to lower forward speed (12.22).

Many different geared steering systems operating on the same principle have been built since then but the next to be tried in Britain was a much more elaborate system installed in the A.6 E.3, the third of the experimental Sixteen-Tonners built in 1928. It consisted of a six-speed compound epicyclic gearbox in the drive to each track the gears of which were changed simultaneously for propulsion while steering was effected by changing down one gear in the box on the side corresponding to the direction in which it was desired to turn (12.23). The tank fitted with it performed well but it was an inefficient system in terms of the number of gears and space and it required the power regenerated at the inner track to be transferred through both gearboxes. Nevertheless, the idea of a twin multi-speed gearbox steering system was taken a stage further in Britain in 1938 with the installation in the A.14 E.1 heavy cruiser tank prototype of two Wilson epicyclic gearboxes with no less than eight speeds.

A more practical form of geared steering was designed in 1931 for the Mark IIA light tank. Like that previously devised for the Mark VIII heavy tank it involved the use of two two-speed epicyclic gearboxes and provided either a geared turn or a skid turn when it acted like a clutch-and-brake system. Its turning circle radius of 9m proved too small but a very similar geared steering system was subsequently successfully adopted in the Covenanter, Crusader and Cavalier cruiser tanks built between 1940 and 1942. In these tanks the steering epicyclics were located at

either end of the layshaft of a transversely mounted four-speed gearbox, which resulted in very compact, integrated transmissions. However, in 1943 they were abandoned in favour of Merritt-Brown transmissions with triple differential steering systems.

In the meantime other geared systems with epicyclics and multiplate clutches had been developed in other countries. The earliest of them appears to have been designed in 1925 by T Hara for the first tank built in Japan. Similar systems giving either a geared turn or a skid turn were subsequently adopted for the Type 89 and all later Japanese medium tanks, including the Type 5 Chiri of 1945.

Another geared system devised in Germany in the late 1920s, which became the subject of Swedish Patent No.78,038 of 1931, led to the steering system of the first tank built in Sweden by the Landsverk Company, the Strv m/31. Later Landsverk tanks also incorporated geared steering. Tanks built in Czechoslovakia during the 1930s by the Ceskomoravska Kolben Danek Company, such as the LTH and its TNHP and Pz.Kpfw.38(t) developments, also incorporated geared steering with a two sun epicyclic train and a multiplate clutch.

By the end of the Second World War the use of geared steering spread to Soviet tanks. The first to have it appears to have been the IS-1 heavy tank. After the war a system providing either a geared turn or a skid turn was also adopted for the T-54 medium tank (12.24). The steering system of the T-54, and also of the T-55 and T-62, consists of an epicyclic gear train and a multiplate clutch on either side of a transversely mounted 5-speed and reverse layshaft gearbox in a manner analogous to that of the steering epicyclics of the Meadows-Wilson and Nuffield-Wilson transmissions of the British cruiser tanks of the early 1940s. In consequence, the transmissions of the Soviet tanks are commendably compact but their crash type gearboxes do not make gear changing any easier than those of the British cruiser tank transmissions.

The latest transmissions to incorporate geared steering are those of the Allison XTG series and in particular the XTG-411-2A which has been fitted in a number of US self-propelled guns produced since 1962, including the widely used 155mm M109 and the 203mm M110. Like almost all the earlier geared steering systems, that of XTG-411-2A provides a geared turn and a skid turn but its hydraulic controls are so arranged that geared turns can only be made when either of its two top forward gears or the high reverse are engaged while clutch-and-brake skid turns can be performed only when the two lowest forward gears or the low reverse are engaged.

The most ingenious geared steering system to have been devised was that incorporated in the German Panther tanks built from 1943 to 1945. The basic features of that system, which was developed at the Maschinenfabrik Augsburg-Nürnberg, are illustrated in Fig.12.10 and its principle of operation has been described already.

The controlled differential, which represented the first advance in differential steering mechanisms on the simple braked differential was originally developed in the United States at the Cleveland Tractor Company. It was the subject of US Patent No.1,254,319 issued in 1918 but tractors incorporating it began to be produced in 1916 (12.25). However, the first tank to be fitted with it appears to have been the Renault NC built to a French Army requirement in 1926. Subsequently almost all French light tanks built up to 1940 were provided with this form of steering which has been known in France as the 'Cleveland differential' whereas elsewhere it is usually called the Cletrac differential, after the trade name adopted by the Cleveland Tractor Company.

Almost simultaneously with its adoption in France, controlled differential steering was also adopted in Germany for the experimental tanks developed in secret by the Krupp and Rheinmetall companies between 1927 and 1930 (12.26). But it was not used in any later German tanks. In contrast, it became widely used in US tanks, although it was first installed in the T1E5 light tank only in 1932. But thereafter it was fitted in almost all US tanks built up to the end of the Second World War, including all the M4 medium tanks and even the heavy, 85 ton T28.

Controlled differential steering then fell out of favour in the United States because of its limitations. But in 1949 its use was revived in France, when it was incorporated in the AMX-13 light tank. In its case the inability of the controlled differential to provide tight turns was overcome by the fitting of additional, track brakes. During the 1950s controlled differential steering began to be used again in the United States, in the M59 armoured carriers, and it continued to be fitted in the M113 armoured carriers well into the 1980s. During the 1960s it was also fitted in the German HS 30 and the British FV 432 armoured carriers and even in the Japanese Type 61 battle tank, which has been the last tank to be built with this form of steering.

It is interesting that the more sophisticated and much more effective double differential system of steering was first tried in a tank before the controlled differential was adopted for any of them. The original double differential steering mechanism was, in fact, designed in France at the Schneider Company under the direction of E Brillié for use in the SRB experimental battle tank, the development of which started in 1921 and in which it was first demonstrated in 1924. The same system was subsequently adopted for the Char B, the first prototype of which was completed in 1929.

The system installed in the SRB and Char B was based on two simple, bevel-type differentials arranged as shown in Fig.12.13. But it was more sophisticated than the mechanism shown, as it had a Naëder hydrostatic pump and motor set to transmit the steering drive from the input of the propulsion gearbox (12.27). In consequence, it enjoyed the advantage of infinitely variable steering control as well as those inherent in double differential steering systems.

The double differential mechanism with a mechanical drive incorporating steering clutches shown in Fig.12.13 illustrates in diagrammatic form the steering system of the French S-35 medium tank designed in 1934 by the Societé d'Outillege Mecanique et d'Usinage d'Artillerie, or SOMUA (12.28). Although not as sophisticated as that of the Char B, the steering system of the S-35 was still well ahead of others. However, it was somewhat bulky and double differential mechanisms which have followed have not been based on bevel differentials but on a combination of two epicyclics. An example of such an epicyclic double differential steering mechanism, which is kinematically equivalent to that shown in Fig.12.13, is shown in Fig.12.14.

An epicyclic double differential steering mechanism was devised in Britain, by W G Wilson, as early as 1928 (12.29). Instead of the steering clutches shown in Fig.12.14 it had two three-speed epicyclic gearboxes and, as the propulsion gearbox had six forward speeds, it provided 3 × 6 turning radii. Wilson's mechanism was never built but in 1938 H E Merritt revived in Britain the idea of an epicyclic double differential steering system. This led to the construction of an experimental transmission which combined such a system with the propulsion gears of a Maybach gearbox and which, consequently, came to be known as the Merritt-Maybach transmission. The latter was tested in the A.16 E.1 heavy cruiser tank

prototype but was abandoned in favour of the Merritt-Brown transmission with a triple differential steering system which was conceived by H E Merritt in 1939. Unlike the Meritt-Maybach transmission, which provided two radii of turn for each of the propulsion gears, the Merritt-Brown transmission provided only one for each of its gears and the gears were still engaged by means of dog clutches. But it was compact, relatively easy to produce and its steering system proved very successful. As a result, it came to be used for many years in almost all British tanks, starting in 1941 with the Churchill infantry tank, most of which had the type H4 transmission with four forward speeds. This was followed, in 1943, in the Centaur cruiser, by the type Z5 with five forward speeds.

Development of epicyclic double differential steering had also started in Germany around 1937 and led to it being incorporated in 1939 in the Henschel L.320 C transmission designed for the experimental VK 3001 medium tank. The L.320 C had a three-speed steering drive taken from the output of the propulsion gearbox, so that it provided only three turning radii, irrespective of which propulsion gear was engaged. But in the Henschel L.600 C and L.801 transmissions which were derived from it and which were produced for the Tiger heavy tanks between 1942 and 1945 the steering drive was taken from the input side of the propulsion gears. In consequence there were 2 × 8 turning radii, as there were two speeds in the steering drive and eight forward gears.

The development of tank transmissions in Germany came to a temporary halt in 1945 and no major advance took place in Britain for several years on the Merritt-Brown transmissions, except for a change from the crash gears to band-brake controlled epicyclic gear trains. This started with the Merritt-Wilson TN-10 transmission and led to the TN12 with six forward speeds which was put into service in the 1960s in Chieftain tanks. A similar but smaller TN 15 transmission with seven forward and reverse speeds was then produced during the 1970s for the Scorpion light tank.

Further major advances took place during the late 1940s and early 1950s in the United States with the development of new transmissions incorporating triple and then double differential steering systems. They originated with attempts to combine the triple differential steering system of the Merritt-Brown transmissions with a hydrokinetic torque converter and associated propulsion gears. The first of the resulting transmissions was designed in 1943 and demonstrated in 1944 in an M26 tank. It was then developed further by the Allison Division of General Motors into the Cross Drive CD-850 transmission, which began to be produced in 1949 for the M46 tanks.

Although the CD-850 followed the example of the Merritt-Brown transmissions in using a triple differential steering system, it differed from them in having a split torque drive arrangement and, therefore, no power circulation. At first its steering drive was taken from the input side of the torque converter, which resulted in steering being affected by the operation of the latter and consequently varying in an unpredictable manner that could be disconcerting to the driver. However, this undesirable characteristic was eliminated in the CD-850-4 and later models in which the steering drive was taken from the output side of the torque converter.

Experience with the CD-850 influenced the design of the next US transmission, the CD-500, which began to be produced in 1950 for the M41 light tank and which was also fitted in the T42 medium tank prototypes. It differed from the CD-850 in having a double, instead of a triple, differential steering system and its steering drive was taken from the start from the output side of the torque con-

verter. The latter was of a similar, single-stage, multi-phase type as that of the CD-850 but it incorporated a lock-up clutch in the interest of greater overall efficiency. However, the CD-500 still had only two forward as well as one reverse gears, or 'ranges'.

The CD-850 and CD-500 were both neatly designed for transverse installation in the hull, with their torque converters and epicyclic propulsion gears coaxial with the output shafts. But they were relatively complex and in 1951 the Ordnance Tank Automotive Command initiated the development of a new, XT series of transmissions which would be simpler, more economical of materials and less costly to produce. They still incorporated torque converters and hydraulically actuated epicyclic propulsion gear trains but these were at right angles to the output shafts, as in the transmissions which preceded the CD-850 and CD-500. Moreover, their design was even more regressive in incorporating clutch-and-brake steering. They were simpler, of course, the XT-500 having 60 per cent fewer parts than the CD-500, in spite of one more forward gear (12.30). But it is difficult to see how the clutch-and-brake steering system incorporated in them could still be considered adequate at that stage of tank development. Deservedly, the XT-500 got no further than the installation in the early 1950s in two of the T42 medium tank prototypes (12.31). Similarly, the XT-300 was only fitted, in the mid-1950s, in the prototypes of the M108 and M109 self-propelled guns.

The abortive development of the XT-500 and XT-300 was followed by that of the XTG transmissions and in particular of the XTG-411-2A which provides a geared turn in addition to clutch-and-brake steering, as well as four forward speeds. The only transmission to be developed in the United States during the 1950s with a more advanced steering system was the XT-1400, which had a double differential system as well as a torque converter with a lock-up clutch, like the CD-500. But its torque converter and the propulsion gear set with three forward speeds were located once again at right angles to the output shafts, so that it took up more space than the CD-850 which it was intended to replace.

No major advance on the Allison CD-500 took place until about 1960 when the Zahnradfabrik Friedrichshafen developed in Germany the 4 HP-250 transmission for the Leopard 1 tank. Like the CD-500, the 4 HP-250 has a torque converter with a lock-up clutch coaxial, together with the epicyclic propulsion gears, with the output shafts and it also has a double differential steering system. But its propulsion gears provide four forward speeds and its steering drive has two speeds, which results in a large and a small radius of turn in each propulsion gear and a total of 2×4 radii when moving forward. Moreover, the steering cross shafts of the 4 HP-250 consist of outer and inner members which interlock the sun gears of the output epicyclics, eliminating differential action between tracks when not steering. This makes for directional stability and is particularly advantageous in muddy terrain or when negotiating obstacles since the loss of traction by one track, which might occur under such conditions, does not bring about a loss of traction by the other track.

Another major advance took place during the late 1950s in Switzerland with the development by the Schweitzerische Lokomotiv und Maschinenfabrik of the transmission for the Pz.61 tank. This consisted of a multi-clutch semi-automatic gearbox with six forward speeds and a double differential steering system with a hydrostatic steering drive developed by von Roll, the first such drive to be produced for a tank since that of the French Char B of the 1930s.

However, the steering system of the Pz.61 with its hydrostatic drive was not the first to be developed since the days of the Char B as another, the LG 600, was

developed in Germany during the Second World War by the Renk Company for the Panther tank (12.32). That system was never put to use but by 1960 Renk had developed another transmission with a double differential steering system and a hydrostatic steering drive for the contemporary *Jagdpanzer Kanone.* This Renk transmission, designated HSWL 123, was followed by the HSWL 194, which was developed in the mid-1960s for the Marder infantry vehicle. In it Renk incorporated a novel form of a split-path steering drive, one part of it being hydrostatic and used for all steering movements while the other is hydrodynamic and brought into action in parallel with the hydrostatic drive by filling in one of two fluid couplings when more rapid turns are required. As the demand for steering torque rises more and more of it is supplied through one or the other of the fluid couplings until they account for more than 60 per cent of it. The split-path hydrostatic-cum-hydrodynamic steering drive is obviously more complicated than a straight hydrostatic drive but it provides the advantages of hydrostatic control with considerably smaller pumps and motors.

In the HSWL 194 transmission the fluid couplings of the steering drive have also been used to provide sustained braking action when a vehicle is running downhill. For this purpose both couplings are filled and the heat generated in them is dissipated through the transmission oil cooling system.

The HSWL 354 transmission developed by Renk during the mid-1960s for the Leopard 2 tank also has a double differential system with a split-path hydrostatic-cum-hydrodynamic steering drive, as well as a two-stage, two-phase torque converter with a lock-up clutch and epicyclic propulsion gears providing four forward and two reverse speeds. As in the HSWL 194, the hydrostatic part of the steering drive consists of a variable displacement pump and a fixed displacement motor, both being of the axial piston type with a swash plate in the case of the pump and a cylinder block set at an angle to the output shaft in the case of the motor. However, in contrast to the HSWL 194, the steering couplings of the HSWL 354 are relieved of the braking function, which is performed by a separate hydrodynamic retarder. Moreover, the retarder is connected to the main transmission cross shaft, so that it can be used to decelerate the vehicle, whereas the steering couplings are driven from the input side of the torque converter, which confines their use as retarders in transmissions like the HSWL 194 to sustained braking. On the other hand, the separate retarder of the HSWL 354 performs 90 per cent of the work involved in braking a vehicle to a stop.

The steering drive in the HSWL 354 and other Renk transmissions is taken from the input side of the torque converter because this gives better low speed steering control. At the same time this has not given rise to the erratic steering behaviour which afflicted the original version of the Allison CD-850, mainly because the torque converters of the Renk transmissions are locked up most of the time whereas the CD-850 does not have a lock-up clutch.

Other contemporary transmissions have not been quite as sophisticated as the Renk HSWL 354 but they have been somewhat less complex. With the exception of the transmissions of Soviet designed tanks, they all have two-phase torque converters with lock-up clutches, epicyclic trains of propulsion gears and double differential steering systems.

Development of the contemporary Allison series of X-transmissions started in 1962 and led in the first instance to the X-700, which was designed for use with engines of up to 800 hp. It reverted to having the epicyclic propulsion gears coaxial with the output shafts, like the CD-850 and CD-500. But its torque converter was separated from them by a long train of gears which divided engine power between

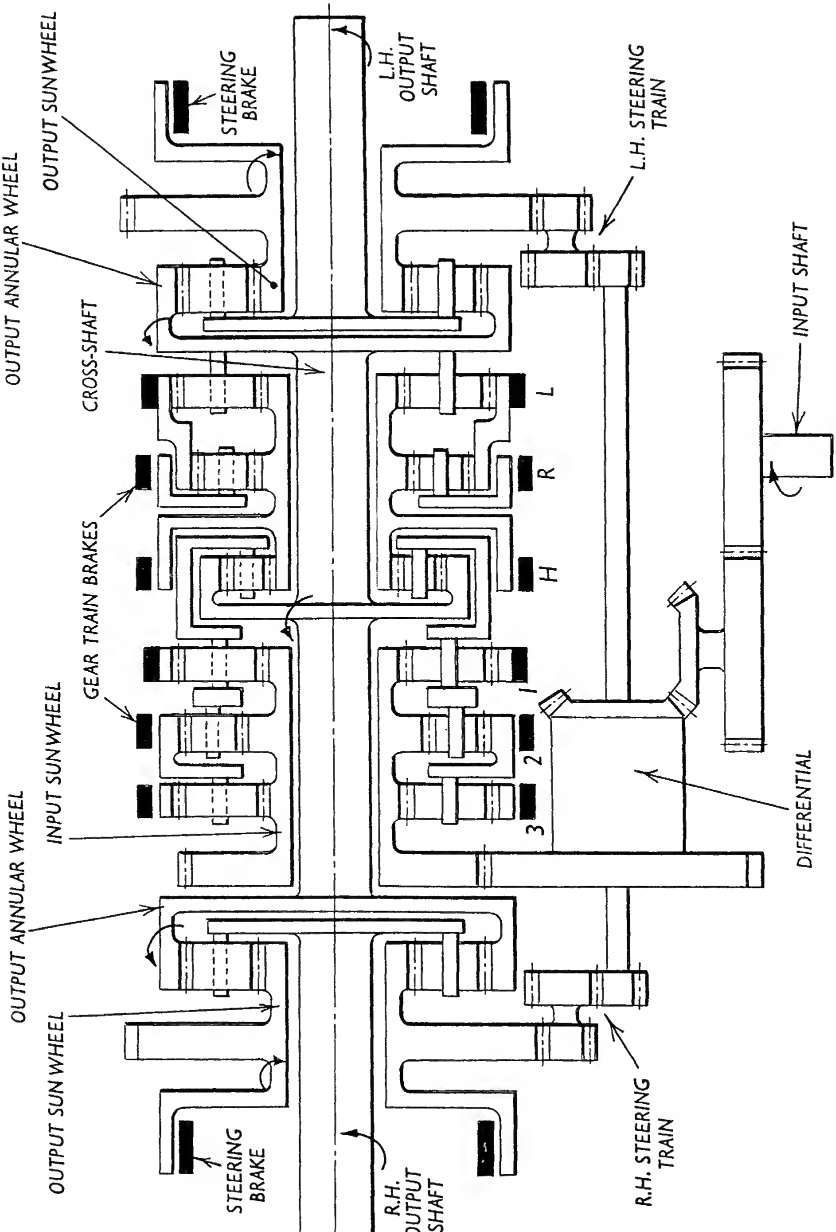


Fig. 12.16 Merritt-Wilson TN 12 transmission.

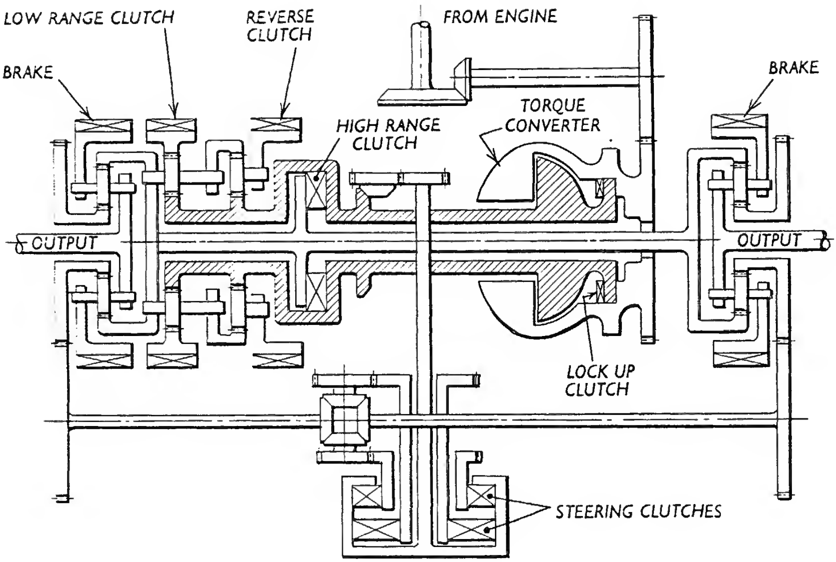


Fig. 12.17 Allison CD-500 transmission.

the propulsion gears and the input gear of its double differential steering system, in the epicyclic trains of which the power was recombined. Moreover, in contrast to the earlier Allison transmissions, the steering drive of the X-700 was hydrostatic, consisting of a variable displacement pump and a fixed displacement motor, both being of the axial piston type.

Seven prototypes of the X-700 were tested from 1964 onwards but it was abandoned in 1972 in favour of the X-1100, which could cope with engines of up to 1500hp and which has been adopted since for the US M1 tank. The X-1100 is simpler than the X-700 and its propulsion gears are parallel with rather than coaxial with the output shafts, while its torque converter is at right angles to them, to suit the traditional, longitudinal location of tank engines. As before, the X-1100 provides four forward speeds but, in contrast to the X-700, there is no splitting of the power flow and the hydrostatic drive of the double differential steering system is taken from the output side of the torque converter. The drive itself consists of a variable displacement pump and a fixed displacement motor, both being of the radial piston type, and is capable of transmitting full engine power (12.33).

In contrast, the TN 37 transmission developed in Britain since 1975 by David Brown Gear Industries and installed in the Khalid and Challenger tanks has its propulsion gear pack coaxial with the output shafts and its hydrostatic steering drive taken from the input side of the torque converter. The same applies to its development, the TN 54, except that the latter has six instead of four forward speeds. The hydrostatic drive of the TN 37 and TN 54 is unusual in containing two pumps and two motors working in parallel, which were adopted because they could be accommodated more easily than a single and inevitably larger pump and motor and because they were considered more suitable for operating at high speeds. All the hydrostatic units are of the axial piston type, the variable displace-

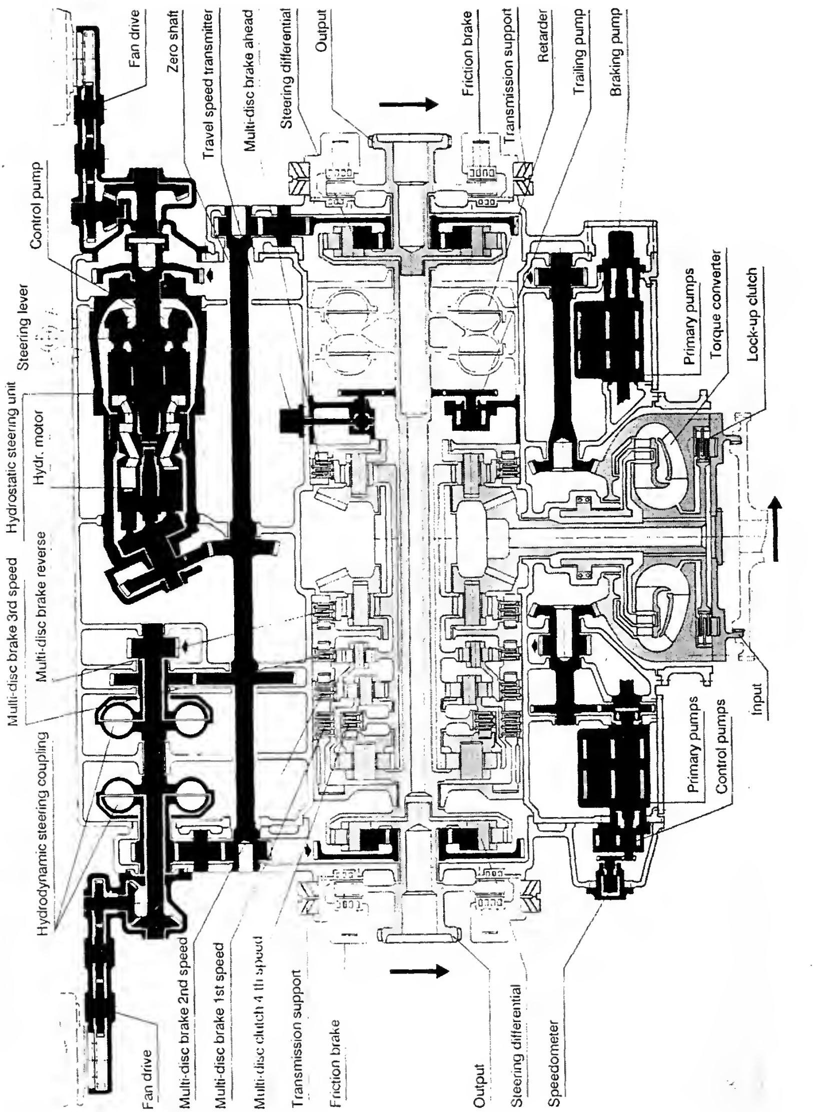


Fig. 12.18 Renk HSWL 354 transmission.

ment pumps having tilting swash plates and the fixed displacement motors having cylinders at an angle to the shaft.

The ESM 500 transmission developed in France by the SESM Company for AMX Leclerc also has its propulsion gears coaxial with the output shafts but its hydrostatic steering drive is taken from the output side of the torque converter and it has a hydraulic retarder similar to that of the Renk HSWL 354. The earlier AMX-30 tank still has the 5 SD 200 D synchromesh gearbox with five forward speeds and a triple differential steering system but its modernised, AMX-30 B2 version has been retrofitted with the ENC 250 transmission which incorporates a torque converter with a lock-up clutch, epicyclic propulsion gears and a double differential steering system with a hydrostatic steering drive.

However, not all of the transmissions developed since the 1960s have hydrostatic steering drives. For instance, the Mitsubishi MT 75 A transmission of the Japanese Type 74 tank has a double differential system with a single-speed mechanical steering drive. What is more, some manufacturers of transmissions with hydrostatic steering drives have developed alternative versions of them with mechanical drives, because they consume less energy and are less expensive. One of them is Renk's RK 304, which resembles the HSWL 194 except that it has a two-speed mechanical steering drive instead of the split-path hydrostatic-cum-hydrodynamic drive. But the RK 304 still has a hydraulic retarder for downhill braking.

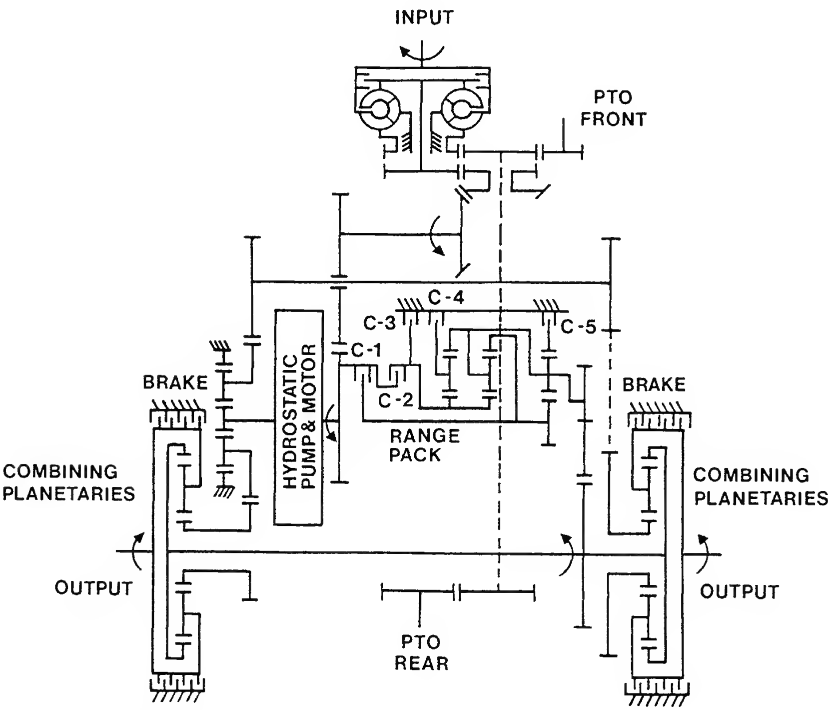


Fig. 12.19 Allison X-1100 transmission.

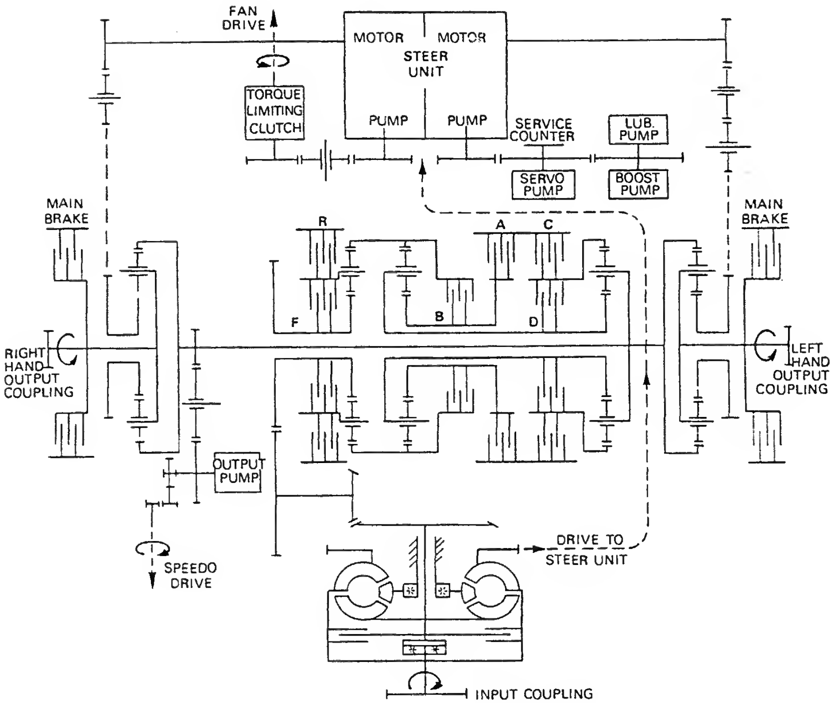


Fig. 12.20 David Brown TN 37 transmission.

Another transmission with a mechanical steering drive, with three speeds, is the LSG 3000 developed by ZF in the early 1980s and adopted for the South Korean Type 88, the Brazilian Engesa Osorio and the Italian C-1 Ariete, as well as being installed in the French AMX-40. The LSG 3000 also has an interlock between its coaxial steering cross-shafts, which eliminates differential action between tracks when the vehicle is not being steered. In addition, it incorporates a hydraulic retarder, which operates like those in Renk's HSWL 354 and SESM's ESM 500. The LSG 3000 also has the customary two-phase torque converter with a lock-up clutch and, like ZF's earlier 4 HP-250 transmission, the steering drive from the input side of the torque converter.

In addition to being used by itself, double differential steering has been combined with clutch-and-brake steering in the system devised by S E Berge and S Henstrom and developed since 1956 by the Bofors Company for the Swedish S-tank. The basic features of this system are shown in Fig.12.23. It incorporates a hydrostatic steering drive the output shaft of which is stationary when running straight ahead with the result that there is no differential action between the tracks. The hydrostatic drive also actuates the first stage of steering, which involves the rotation of the sun gears of the output epicyclics in opposite directions and results in one track going slower and the other correspondingly faster, as with other double differential steering systems.

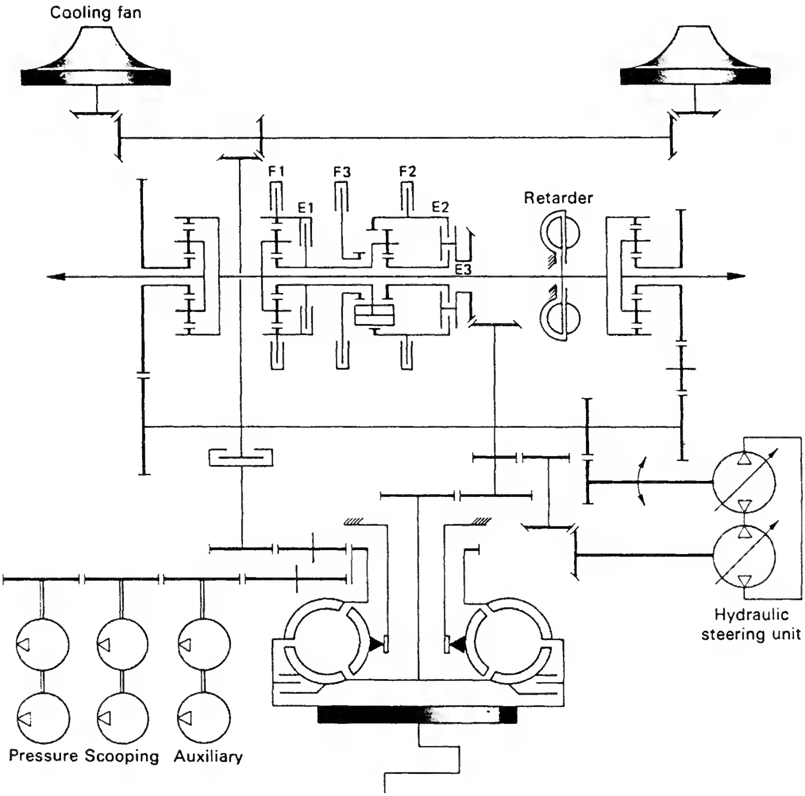


Fig. 12.21 ESM 500 transmission.

Movement of steering controls beyond the first stage causes disengagement of the clutch in the drive to the inner track, and the application of the brake on that side. This brings to rest the annulus in the corresponding output epicyclic but the output shaft on the same side continues to rotate, although slowly and in reverse. In consequence, in the second stage of steering, the system behaves like a geared system with a large step-down and causes a reduction in the mean speed of the tracks. This implies a change in the momentum of the tank, which helps to initiate a turn and leads to rapid changes of direction that are particularly important to a turretless vehicle with a fixed gun like the S-tank.

In its second stage of operation the steering system of the S-tank differs from geared systems and from its performance in its first stage in not being regenerative, because the inner track is driven in the same direction as the ground forces acting on it. However, the second stage of operation is used far less frequently than the first and generally for short periods so that its non-regenerative nature is not a major disadvantage.

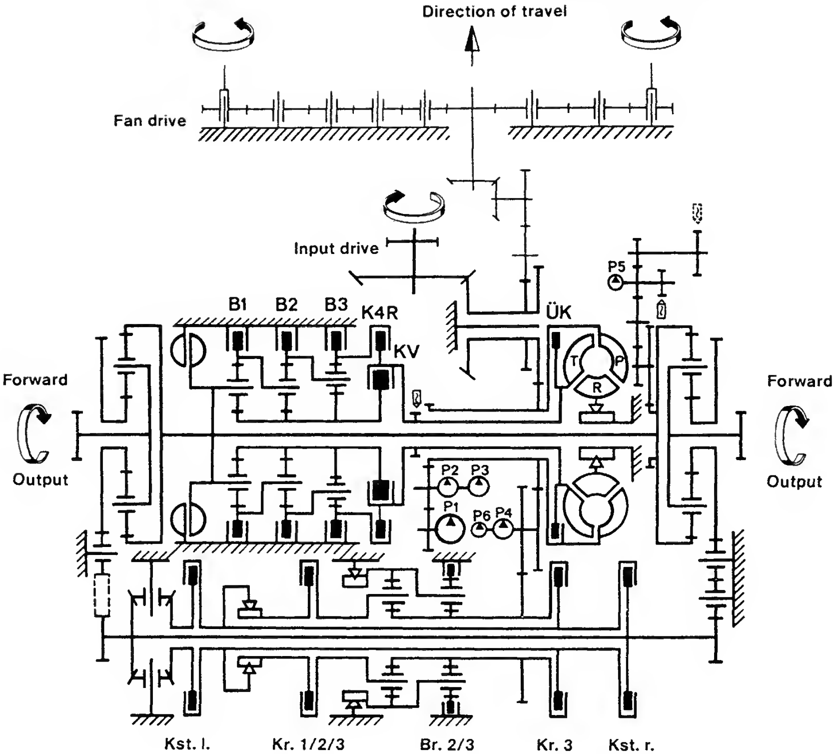


Fig. 12.22 ZF LSG 3000 transmission.

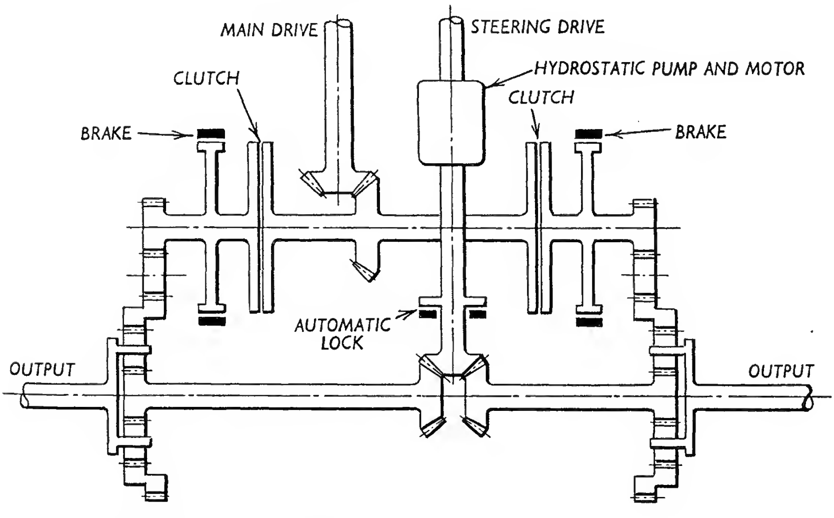


Fig. 12.23 Basic features of S-tank's steering system.

12.7 Hydrostatic and Hydromechanical Transmissions

Before they began to be used for steering drives, attempts were made to use hydrostatic transmissions for propulsion. The first was as early as 1917, when a British Mark IV tank was fitted with a Williams-Janney hydrostatic transmission (12.34). This was based on axial piston pumps and motors which were being used already in ships, particularly for controlling rudders, and it consisted of two such positive displacement pumps and two fixed displacement motors, each of the latter being connected by gears to the track sprocket on its side.

The system provided infinitely variable propulsion and steering and made the Mark IV tank easy to drive, as well as being regenerative, subject, of course, to the efficiencies of its hydraulic elements. Trials with it were successful and it was adopted for the Mark VII tank. However, only three of it were built in 1918 (12.35). Three years later a Williams-Janney hydrostatic transmission was used again, this time in Vickers' first light tank. But this was abandoned in 1922 after only two had been built. It then took 22 years to fit another tank with a hydrostatic transmission. The tank was a German Pz.Kpfw.IV which was fitted with an experimental Thoma hydrostatic transmission. Like the Williams-Janney, this consisted of two variable displacement axial-piston pumps connected by pipes to two separate axial-piston motors which drove the tracks through the rear sprockets.

The Pz.Kpfw.IV with its Thoma transmission was examined after the Second World War in the United States but almost 20 years had to pass again before another attempt was made to develop a transmission for tanks based on hydrostatic pumps and motors. The attempt was sponsored by the US Army Tank-Automotive Command and the development was carried out by the Allison Division of General Motors, who started working on it in 1964. The outcome of it was the XHM-1500-1 hydromechanical transmission, in which hydrostatic pumps and motors were combined in parallel with gear trains. As a result, some of the power flowing through it could be transmitted mechanically instead of all being transmitted hydraulically, as in the earlier hydrostatic transmissions. This reduced the effects of the relative inefficiency of the hydraulic units on the overall efficiency of the transmission, which had been unacceptably low with the earlier, purely hydrostatic transmissions and made the XHM-1500-1 transmission more competitive with others. The epicyclic gear trains incorporated in it also extended the torque multiplication provided by the transmission well beyond what the hydrostatic pump and motor sets can usefully provide by themselves, which is of the order of 5:1 at full load. At the same time the hydromechanical transmission offered virtually the same advantages of infinitely variable drives and ease of control as the hydrostatic transmissions.

The XHM-1500-1 resembled the hydrostatic transmissions which preceded it in providing a separate drive for each track, although this incorporated gears and clutches as well as a variable displacement pump and a fixed displacement motor. In the first range of the transmission the drive was still wholly hydrostatic but in the second and third ranges the power flow was divided between a hydraulic path through the pumps and motors and a mechanical path through the gears, which reduced the magnitude of the power losses incurred in the hydraulic units, the power then being recombined in the output epicyclic gear trains (12.36).

The provision of an independent, infinitely variable drive for each track offered infinitely variable steering but it also made the consistency of directional control

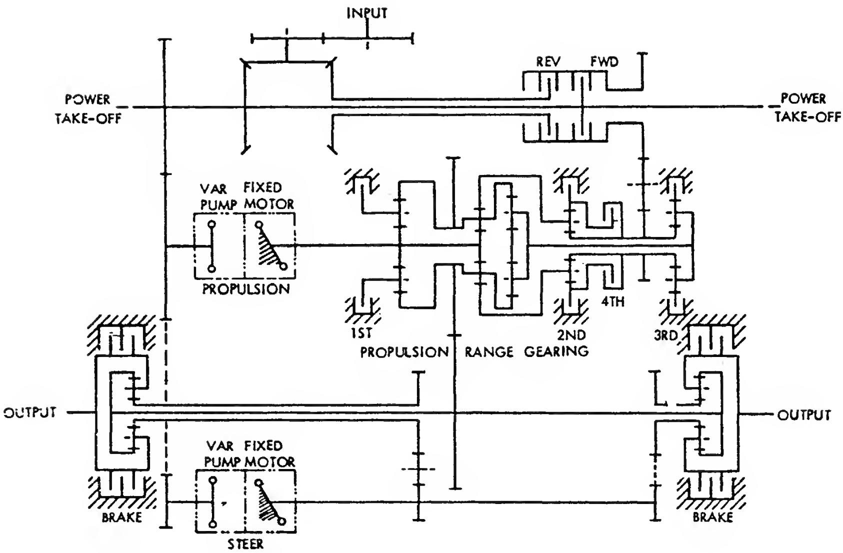


Fig. 12.24 Allison XHM-1500-2 hydromechanical transmission.

vulnerable to differences between the characteristics of the two drive lines and consequently erratic. As a result, Allison abandoned the use of an independent drive for each track and developed the XHM-1500-2 with separate propulsion and steering drives. Thus, XHM-1500-2 came to consist of a hydrostatic pump and motor unit and a three-speed epicyclic gear set which provided a hydromechanical propulsion drive and of a separate hydrostatic steering drive which formed part of its double differential steering system.

As before, the hydrostatic units were all of the swash-plate driven axial-piston type but the variable displacement pump and the fixed displacement motor of the steering drive were smaller than the corresponding units used for propulsion. In the first range of the transmission the drive was again purely hydraulic but in the other three ranges only part of the power was transmitted hydraulically and the rest mechanically.

The infinitely variable characteristics of the XHM-1500-2 made it very suitable, in theory, for use with gas turbines and much of the incentive to develop it came from the emergence of the Avco-Lycoming AGT-1500 as a possible engine for the US XM803 battle tank. However, after it was built in 1971 it turned out to be significantly heavier as well as more bulky and less efficient than the contemporary Allison X-1100 hydrokinetic transmission which was in the same power category. In consequence, the XHM-1500-2 was abandoned but other, smaller hydromechanical transmissions continued to be developed by the General Electric Company.

Development of hydromechanical transmissions by General Electric started in the early 1960s and was based on its experience with hydraulic drives for naval gun turrets and aircraft alternators (12.37). These incorporated a novel type of hydrostatic pump and motor with radial cylinders and ball pistons, the stroke of which is

varied by altering the eccentricity of the outer casing in relation to the cylinder block when they are used as variable displacement units. One of the attractions of ball-piston pumps and motors is that they lend themselves to being assembled into close-coupled sets and they became the basis of a series of General Electric hydromechanical transmissions, which led to the HMPT-500 developed from 1972 onwards for the US XM723 Mechanized Infantry Combat Vehicle and its derivative, the M2 Infantry Fighting Vehicle.

Like the experimental General Electric transmissions which preceded it, the HMPT-500 has a ball-piston variable displacement pump and fixed displacement motor to drive each track and an epicyclic gear train which transmits mechanically a part of the engine power to the epicyclic gears at the output shafts, where that power is recombined with the power transmitted by the hydrostatic units. The output epicyclics are connected by a cross shaft and when this is locked in the first range of the transmission and in reverse all engine power is once again transmitted by the hydrostatic units. But in the second range only 45 per cent of the power is transmitted by them and in the third range, which is commonly used for road operation, the percentage is only 20. This leads to a relatively high overall efficiency of the HMPT-500, which reaches 85 per cent at full power in the third range and is above 80 per cent for most of the speed range.

Within each range the output-to-input torque ratio can be infinitely varied by simultaneously altering the displacement of the two ball-piston pumps. Steering radius can be similarly varied by altering the displacement of the pumps relative to each other to the point where the tracks are driven in opposite directions and the vehicle executes a pivot turn. As with other hydromechanical transmissions, the steering of the HMPT-500 is regenerative and its infinitely variable characteristics are used to minimise the overall fuel consumption of the vehicle by means of a

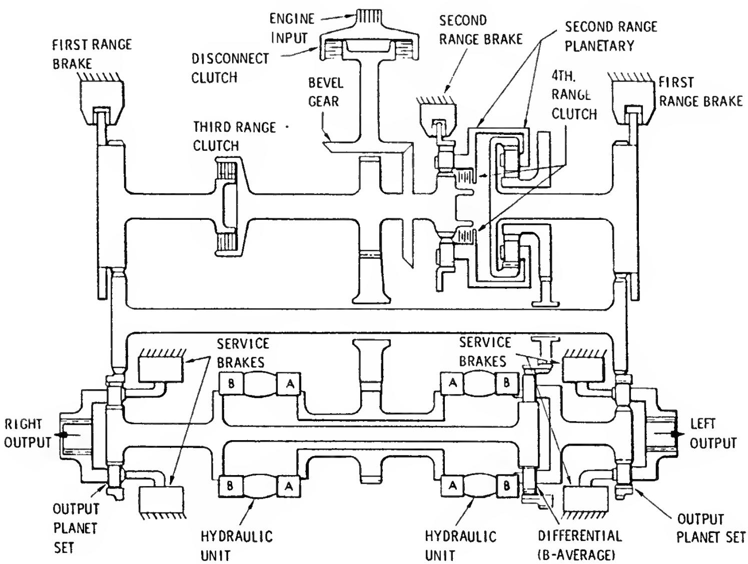


Fig. 12.25 General Electric HMPT-500 transmission.

governor which alters the transmission ratio so as to maintain an optimum engine speed for a given power. Like other hydromechanical transmissions, the HMPT-500 can also transmit power in reverse, which makes the engine coupled to it available for braking at all times and it can be used to steer a vehicle with a dead engine. At the same time it is no heavier and no more bulky than other transmissions of the same capacity and it contains a relatively small number of parts, which helps reliability.

All this together with extensive comparative trials led the US Army to adopt the HMPT-500 in 1977 for the M2 Infantry Fighting Vehicle in preference to the X-300 hydrokinetic transmission. As a result it has been produced in quantity since 1981 for the M2 IFV and its derivatives and it has also been installed in at least three different light tank prototypes.

12.8 Electric Transmissions

Electric transmissions began to be used in tanks almost as soon as they started to be developed. But the use of electric transmissions has been very limited and there has only been occasional interest in them, in spite of advances in electric transmission technology.

The first electric transmission to be used in tanks was installed as early as 1916 in the prototype of the second type of tank to be developed in France, the St. Chamond. Four hundred St. Chamond tanks were subsequently produced for the French Army and their Crochat-Collardeau transmission consisted of a DC generator coupled to the engine and of two DC motors, each driving a track through reduction gears. The speed of the two motors and hence of the tracks could be varied independently of each other, which made it easy to steer the tank (12.38).

In 1917 two British Mark IV tanks were tried with Daimler and Westinghouse electric transmissions (12.39). A year later the Holt Tractor Company built in the United States an experimental tank with a General Electric transmission and electric transmissions were also adopted for the two 148 ton K-Wagen which were being constructed in Germany in 1918, although they were never completed. Moreover, before the end of the First World War the Forges et Chantiers de la Mediterranée. (FCM), began to build the 2C heavy tanks with electric transmissions.

However, only ten of the 68 ton 2C were completed, in 1921, and until 1940 they were the only tanks in use with an electric transmission, as well as being the heaviest. The reason for the lack of interest in electric transmissions during the intervening period was that their advantages were outweighed by their disadvantages. In particular, they offered the very favourable torque-speed characteristics of their DC traction motors and infinitely variable and independent control of tracks speeds, which made tanks fitted with them easier to drive than with other contemporary transmissions. But this was more than offset by their relatively heavy weight, large bulk and low efficiency.

Nevertheless, after the outbreak of the Second World War there was a revival of interest in electric transmissions, which offered a relatively simple and quick answer to the transmission requirements of heavy tanks. Thus, in 1940 and 1941 they were installed in two prototypes of the British TOG heavy tank, which weighed 63.5 and 80 tons. Both had two generators driven directly by the tanks' engines and two DC motors each receiving power from its respective generator and driving one track independently of the other. However, when turning the

motor connected to the inner track acted as a generator and the power regenerated by it was passed through the generator connected to it to the other motor, which increased the turning moment, although the efficiency of the power regeneration was low.

Electric transmissions were also adopted for the VK 3001(P) medium and VK 4501(P) heavy tank prototypes developed in Germany between 1940 and 1942 under the direction of F Porsche. Neither type of tank was adopted but they served as the basis of the 65 ton Ferdinand heavy tank destroyer, 90 of which were produced in 1943 and which were used by the German Army during the latter part of the Second World War. An electric transmission was also adopted for the 188 ton Maus heavy tank, two prototypes of which were built in Germany between 1943 and 1944.

Like that of the Ferdinand, the electric transmission of the Maus consisted of two generators each connected, via a variable resistance operated by a steering lever, to a motor driving one of the track sprockets. As in the British TOG, the motors could act as generators, so that the motor on the inside of a turn regenerated power which was transferred to the other motor. The electric transmissions of the German vehicles proved relatively reliable but their efficiency was low, particularly when regenerating power during turns, and their power losses caused cooling problems. Moreover, they were heavy and bulky, due to a large extent to the size of the motors, each of which had to be capable of transmitting not only the whole of the engine power but also the power regenerated by the other motor during turns.

Similar comments apply to the electric transmissions developed between 1941 and 1943 in the United States by the General Electric Company. They were developed first for the T1E1 heavy tank prototype and then for the T23 medium tank, 252 of which were built in 1943 and 1944 but none of which was ever put into service.

The General Electric transmissions of the T1E1 and T23 tanks were the last and the most highly developed of the all-direct current tank transmissions. Like some of the earlier transmissions, they consisted of a single generator coupled to the engine and of a motor at each track. But the motors as well as the generator were provided with amplidynes to control their field strength and steering was accomplished by varying the field strength of one motor in relation to the other. For tight turns the field current of the motor on the inside of the turn was reversed, making it act as a generator and supply current to the other motor. In the extreme the two tracks could be driven in opposite directions to produce a pivot turn.

No further attempt to use electric transmissions in armoured vehicles was made until the 1960s, when there was a revival of interest in them in the United States prompted by progress in electrical technology and the requirement for new transmissions for use with the gas turbines which were emerging as possible tank engines. In particular, in 1961 General Electric proposed to the US Army's Ordnance Tank-Automotive Command a number of new electric transmissions for tanks. The simplest of them involved the replacement of the DC generator used in the earlier transmissions by a high speed, high frequency alternator, which was smaller and lighter and which dispensed with the brushes required by DC machines (12.40). The output of the alternator was to be rectified to supply electrical power in a form suitable for series-wound DC motors which were retained, in spite of their weight, because of their high starting torque and almost hyperbolic torque-speed characteristics.

No transmission of this kind was built for tanks in the United States but in

Belgium the Ateliers de Constructions Electriques de Charleroi, (ACEC), produced one of its type for the wheeled armoured vehicles of the Crotale surface-to-air missile system developed in France during the mid-1960s. The transmission of the Crotale system was based on ACEC's experience with electric transmissions for railways and buses and it was adopted partly because it enabled a single electrical power system to provide power either to drive the vehicles or to operate the radar or missile launch systems mounted in them.

Vehicles of the Crotale system began to be produced in 1970 and concurrently with the construction of their first prototype in 1967 ACEC installed an electric transmission similar to theirs in the chassis of a US-built M24 light tank. Experience with this vehicle and in France with an AMX-10 armoured carrier fitted with their transmission led ACEC to design a tracked armoured vehicle which would incorporate an electric transmission from the start and more fully demonstrate its advantages. This led to the Cobra armoured carrier, the first prototype of which was completed in 1978. Its electric transmission includes a pancake-type alternator with a built-in rectifier which is attached directly to the front-mounted engine and takes up little more space than the flywheel and clutch it replaces. The transmission also includes two high-speed, geared DC motors mounted at the rear of the hull under the benches of the personnel compartment. In this way ACEC minimised the amount of space occupied within a vehicle by the transmission and improved the weight distribution by mounting the motors away from the engine.

The weight of the electric transmission of the Cobra is no less than that of an equivalent mechanical transmission but the relatively low inertia of its rotating parts, together with the torque-speed characteristics of its motors results in good acceleration from a standing start. At the same time the transmission is relatively efficient. Thus, the peak efficiency of its alternator is 92 to 93 per cent and of its motors 85 to 86 per cent, which gives an overall efficiency of about 79 per cent and makes the electric transmission of the Cobra competitive with other types of transmissions.

In order to keep down its cost, the transmission of the Cobra has been made as simple as possible. One consequence of this, which has helped to keep down the size of its motors, is that it does not regenerate power from the track on the inside of a turn. Instead, it merely distributes engine power between the two motors, in the limit directing all of it into the outer motor and if a tight turn is required a brake is applied to the inner track. In this respect the steering system of the Cobra is no better than the clutch-and-brake system of mechanical transmissions. However, the rotation of the motors can be reversed and when they are made to operate in opposite directions the Cobra can execute a pivot turn.

Another of the transmissions proposed in 1961 by General Electric was to take advantage of the advent of silicon controlled rectifiers to use not only an alternator but also AC squirrel cage induction motors, which would be lighter than DC motors as well as being brushless. At the same time the AC motors would have characteristics similar to those of DC traction motors as a result of an appropriate control of their supply voltage and frequency. This involved supplying the rectified output of the alternator to two silicone controlled inverters which converted the DC input into the required AC output and varied its frequency to control the speed and torque of the corresponding motors. Commanding a difference between the frequencies of the supply to the motors caused them to rotate at different speeds and consequently provided steering control. When steering, the motor commanded to run at a lower speed acted as an induction generator and power

regenerated by it was fed through the inverters to the other motor.

In the late 1960s a transmission of this kind was actually built in the United States by FMC Corporation and was tested in an M113 armoured carrier. Based on the ratio of motor output to alternator input, it had a peak electrical system efficiency of more than 80 per cent and its overall efficiency was broadly comparable to that of the hydrokinetic transmission normally fitted in the M113. However, it was heavier and its bulk was considerably greater, due to the size and weight of the inverters and the associated control equipment (12.41).

A third type of electric transmission proposed in the United States in the early 1960s dispensed with the DC link, which involved the use of a rectifier and inverters. Instead it fed the output of the alternator directly into two silicone controlled rectifier frequency changers, or cycloconverters, which supplied variable frequency power to induction motors. The output frequency of the cycloconverters was controlled individually to provide the appropriate torque for propulsion and for steering. As before, there was regeneration of power when turning and the system provided pivot turns.

A transmission of this type was built in the mid-1960s by FMC Corporation and was installed in an articulated wheeled vehicle. However, it did not advance beyond trials and other work on electric transmissions, which was sponsored by the US Army Tank-Automotive Command, was discontinued in 1974 for financial reasons.

Nothing more happened until about 1980 when new AC transmissions were proposed in the United States and they were to take advantage of the development of rare earth permanent magnet motors. In particular, Garrett proposed a system which still used a rectifier and inverters but incorporated samarium-cobalt permanent magnet motors. At about the same time General Electric proposed another system which combined permanent magnet synchronous motors with cycloconverters.

Neither of the proposed systems was adopted but FMC took advantage of progress made in reducing the size of the electronic power conditioning and motor control equipment to produce a much more compact version of their transmission involving the use of induction motors. By 1989 this had been successfully demonstrated in a M113 armoured carrier, which encouraged further work on electric transmissions for tracked armoured vehicles. At about the same time an electric transmission was also installed in Germany in a Marder armoured infantry vehicle.

In addition to the development of new, more compact and more efficient components, another reason emerged during the 1980s for considering the use of electric transmissions. This has been the development of electromagnetic and electrothermal guns which, together with the increasing use of electric drives for tank turrets and other subsystems, led to the concept of the 'all-electric' tank. Such a vehicle would have a single, electrical source of power consisting of an engine driven generator which would supply power, as required, to launch projectiles, to drive the vehicle, to traverse the turret and even to activate electromagnetic protection against some forms of attack, such as shaped charge jets.

12.9 References

12.1 G V Cleare, 'Tank Transmission Development: Part I', *Journal of Automotive Engineering*, Vol.4, No.5, October 1973, pp.21-24.

12.2 C A Cheyne, 'Automatic Transmissions in America', *Proc. Automobile Div., Inst.*

Mech. Engrs., Part I, 1952-53, pp.9-15.
12.3 J G Giles. *A Review of Hydrokinetic Fluid Drives and Their Possibilities for the British Motor Industry*, Proc. Automobile Div., Inst. Mech. Engrs., No.2, 1956-57.
12.4 C A Cheyne. op.cit., p.12.
12.5 E Gray, 'Tank Engine Development', *Ordnance*, Vol.46, No.250, January-February 1962, pp.590-592.
12.6 *An Illustrated Record of the Development of the British Armoured Fighting Vehicle, Tanks 1915-1918*, RAC Tank Museum, Bovington Camp, 1967, p.57.
12.7 G le Q Martel, *In the Wake of the Tank*, Sifton Praed, London, 1931, pp.84-88.
12.8 L F Little, 'The Alecto Tracklayer', *Journal of Terramechanics*, Vol.1, No.2, 1964, pp.76-82.
12.9 'Commercial Motor Vehicle Exhibition', *The Engineer*, Vol.116, July 25, 1913, pp.97 and 99.
12.10 M Sueter, *The Evolution of the Tank*, Hutchinson, London, 1937, pp.77-80.
12.11 R M Ogorkiewicz, 'Articulated Tracked Vehicles', *The Engineer*, Vol.212, No.5522, November 24, 1961, pp.849-854.
12.12 W Steeds, 'Tracked Vehicles', *Automobile Engineer*, Vol.40, No.4, April 1950, p.144.
12.13 H E Merritt, 'Some Considerations Influencing the Design of High-Speed Track-Vehicles', *Proc. Inst. Automobile Engineers*, Vol.33, 1938-39, pp.420-421.
12.14 W Steeds, op.cit., p.146.
12.15 H E Merritt, 'The Evolution of a Tank Transmission', *Proc. Inst. Mech. Engrs.*, Vol.154, No.4, 1946, p.413.
12.16 W Steeds, ibid., pp.144-48.
12.17 J R Ray, *Investigation of the Factors Involved in Steering Tracklaying Vehicles*, Technical Report No.10, 969, US Army Tank-Automotive Command, Warren, 1970.
12.18 G V Cleare, op.cit., Part II, December 1973, p.30.
12.19 R B Gray, *Development of the Agricultural Tractor in the United States*, Part I, American Society of Agricultural Engineers, St. Joseph, 1956, p.43.
12.20 E H Tennyson d'Eyncourt, 'Account of the British Tanks used in the War', *Engineering*, Vol.108, No.2802, 12 September, 1919, p.338.
12.21 A G Stern, *Tanks 1914-1918*, Hodder and Stoughton, London, 1919, pp.271-272.
12.22 E H Tennyson d'Eyncourt, op.cit., No.2803, 19 September, 1919, p.371 and Plate XX.
12.23 G V Cleare, op.cit., Part I, pp.22-22.
12.24 F M von Senger und Etterlin, *Der Sowjetische Mittlere Kampfpanzer der Baureihe T-34 bis T-62*, Lehmanns, Munich, 1970, p.40.
12.25 R B Gray, op.cit., p.45.
12.26 W Esser, *Dokumentation über die Entwicklung und Erprobung der Ersten Panzerkampfwagen der Reichswehr*, Krauss-Maffei, Munich, c.1979.
12.27 *Char B1 bis: Notice sur la Description et l'Entretien de Materiel*, Atelier de Construction de Rueil, 1939, Figs. 22, 29 and 30.
12.28 *Notice Descriptive du Char 1935 S*, SOMUA, Saint-Ouen-sur-Seine, 1938, pp.22-23.
12.29 H E Merritt, op.cit., contribution to discussion by W Steeds, p.423.
12.30 E Hamparian, *The Evolution of Power Trains and Steering in High Speed Military Track Laying Vehicles*, SAE Paper No.670726, Soc. Automotive Engrs., New York, 1967, p.9.
12.31 R P Hunnicutt, *Patton*, Presidio Press, Novato, 1984, pp.46-47.
12.32 R G Reppert, 'Modern Transmissions for Tanks', *Military Technology* Vol.11, No.4, 1987, Special Supplement, p.13.
12.33 J W Schmidt and G L Hadley, *The New X1100 Automatic Transmission for the XM1 Tank*, SAE Paper No.770339, Soc. Automotive Engineers, Warrendale, 1977.
12.34 A G Stern, op.cit., pp.263-264.
12.35 E H Tennyson d'Eyncourt, ibid., pp.337-339 and Plate XIX.
12.36 E Hamparian, op.cit., pp.22-25.

12.37 R J Dorgan, R L Rio and D M Latson, *Development of a Hydromechanical Steering Transmission*, SAE Paper No.720726, Soc. Automotive Engineers, New York, 1972.
12.38 L Dutil, *Les Chars d'Assaut*, Berger-Levrault, Nancy, 1919, pp.19-20.
12.39 A G Stern, ibid., pp.106-107 and 267-270.
12.40 *A Proposal for Electric Drive System for 45 ton Track Laying Vehicle*, GE File No.90009, General Electric Defense Systems Department, 1961.
12.41 J A Kirtland, D C Andrus and W Slabiak, *An AC Electric Drive System as Applied to a Tracked Vehicle*, SAE Paper No.690442, Soc. Automotive Engineers, New York, 1969.

12.10 Supplementary Bibliography

The Automotive Assembly, AMCP 706-365, US Army Materiel Command, Washington, 1962.
W Esser, *Die Panzerkampfwagen unserer Gegner*, ATZ, Vol.46, No.17/18, 25 September 1943, pp.399-426.
W Merhof and E M Hackbarth, *Fahrmechanik der Kettenfahrzeuge*, Leuchturm-Verlag, Alsbach, 1982.
R M Ogorkiewicz, *Design and Development of Fighting Vehicles*, Macdonald, London, 1968.
R M Ogorkiewicz, 'New ZF Tank Transmissions', *International Defense Review*, Vol.21, No.9, 1988, pp.1171-1173.
R M Ogorkiewicz, 'Renk Transmissions for Armoured Vehicles', *International Defense Review*, Vol.22, No.2, 1989, pp.209-212.
W E Rodler and K W Shafer, *Electric Drive Study*, Vol.1, R D & E Center Technical Report No.13236, US Army Tank-Automotive Command, Warren, 1987.

Chapter 13

Suspensions and Running Gear

13.1 Human Response to Vibrations

The surfaces over which tanks move are generally uneven. In consequence they give rise to vibrations which affect the crews and which can seriously degrade or restrict their performance. The severity of the vibrations depends in the first instance on the geometry and hardness of the surfaces over which tanks move and on the speed of tanks. However, it also depends on the suspensions of tanks, which are intended to minimise the displacements and the forces experienced by them.

The nature of the surfaces which cause the vibrations varies considerably. Some are the rough surfaces of roads while others consist of the undulating surfaces of soft soils but the most difficult, from the vibrations point of view, are represented by broken, hard ground, which can severely restrict the speed of tanks over it. Restrictions on speed can also be imposed by discrete terrain features, such as ditches.

Since the effects of the uneven surfaces on tanks are ultimately related to the reactions of their crews, they involve the human response to vibrations. The subject has been studied extensively and various attempts have been made to establish limits of human vibration tolerance (13.1). Such limits are of direct interest in relation to the speed of tanks over rough ground because their crews generally restrict it to the degree of discomfort or risk of injury they are prepared to accept. However, there is no general agreement on what these limits are, although some of those put forward have gained a fair degree of acceptance.

The most frequently studied aspect of the subject has been the response to vertical vibrations. An outcome of the studies of it has been data on the variation of the acceptable amplitude of vertical vibrations with their frequency. Data on this from a number of sources has been correlated by R N Janeway and presented in the form of three simple relationships which cover the frequency range of 1 to 60Hz (13.2). According to these relationships, which are called after Janeway and which have been recommended within the automotive industry, the acceptable amplitude of vertical vibrations decreases rapidly with frequency, from about 50mm at 1Hz to less than 0.01mm at 60Hz.

To relate this to the movement of tanks over rough ground, the frequency of the vibrations can be equated with their speed and the displacements may be taken to be proportional to the amplitude of the irregularities of the ground. Studies of the response to vertical vibrations then lead to the conclusion that the maximum speed of tanks should decrease with the roughness of the ground in much the same

way as the frequency of the vibrations considered decreases with their amplitude. In fact, this has proved to be the case as shown in Fig.13.1, which is based on results obtained under conditions where vehicle speed was limited by surface roughness (13.3).

The results illustrated in Fig. 13.1 are presented in terms of vehicle speed versus surface roughness defined in terms of the root mean square (RMS) of the elevation of the ground profile because of its random nature. The physical meaning of the RMS values may be gauged from the fact that a surface with an RMS elevation of 25mm would be regarded as 'smooth', while one with a value of about 60mm would be 'fairly rough' and with 90 to 100mm 'extremely rough'.

The pattern of the results illustrated in Reference 13.3 and Fig. 13.1 suggests that vertical displacements at the crew stations should be taken as a criterion of the vibration tolerance of tank crews. In fact, some studies have related them directly to the maximum speed of vehicles over rough ground. As a result a total or peak-to-peak displacement of about 100 to 130mm has been suggested as the maximum acceptable (13.4). This value of maximum displacement was meant to

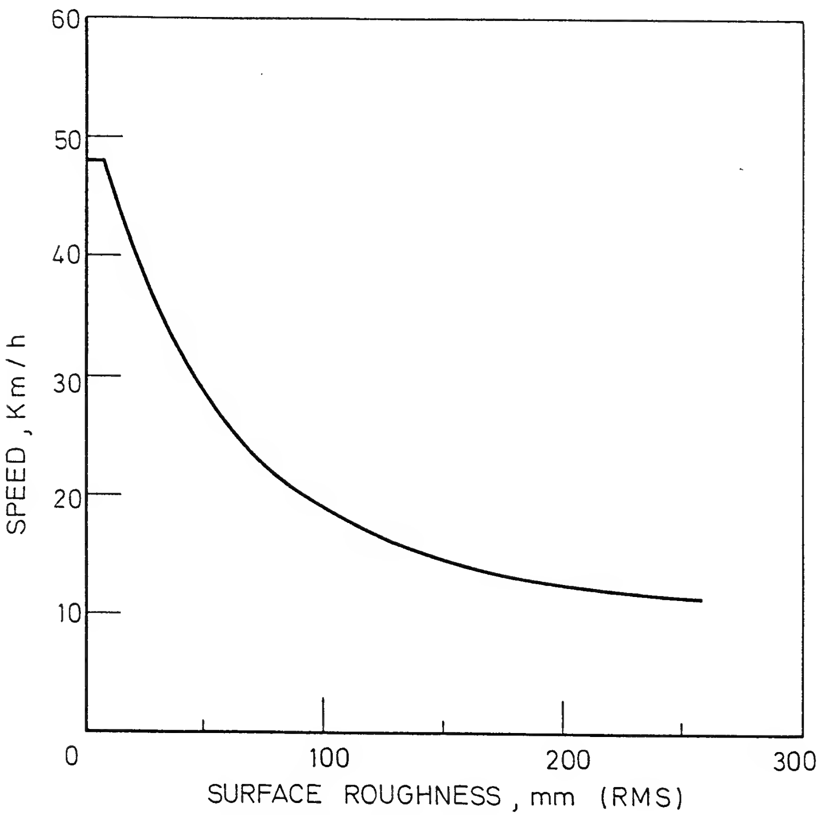


Fig. 13.1 Speed of a US M60 tank versus surface roughness.

apply at very low frequencies and in their realm it corresponds roughly to the results of the studies, mentioned earlier, of the responses to vertical vibrations.

An alternative criterion of vibration tolerance has been acceleration and particularly vertical acceleration at the crew stations. A major point in favour of it is that acceleration is relatively easy to measure in vehicles (13.5). Moreover, the amplitude of the acceleration is proportional to the product of the amplitude of the displacement and the square of the circular frequency, while the acceptable displacement decreases exponentially with frequency. As a result, the maximum acceptable acceleration might be expected to vary less with frequency than other possible measures of vibration tolerance, which would favour its use as such.

However, test results show that the acceptable acceleration varies significantly with frequency in the 1 to 100Hz range which is of interest in relation to vehicles. In consequence, when acceleration is used as a limit of vibration tolerance this can not be done in terms of a single value but needs to be expressed as function of vibration frequency. This is done in International Standard ISO 2631 on human

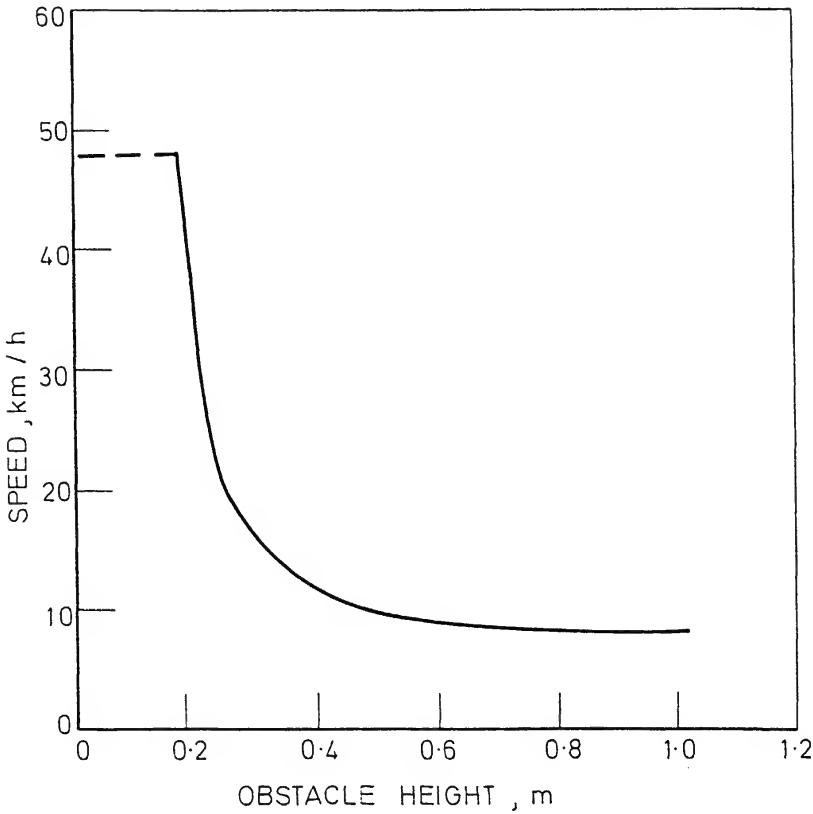


Fig. 13.2 Speed of a US M60 tank corresponding to a vertical acceleration of 2.5g versus height of obstacles.

exposure to whole body vibration in the form of curves of maximum acceptable acceleration versus frequency. Moreover, ISO 2631 recognises the time dependence of human response to vibrations and, consequently, contains curves for different durations of exposure to vibration; the longer the exposure the lower being the curve of acceptable acceleration (13.6).

In addition to being used directly as a measure of the vibration tolerance, acceleration has also been used to determine the power absorbed by human bodies exposed to vibrations, which has become widely accepted as another criterion of the vibration tolerance of tank crews. In fact, the absorbed power is equal to the product of the square of the RMS value of the acceleration and of a constant which is dependent on frequency (13.7).

The use of absorbed power as a criterion of the vibration tolerance is based on tests at the US Army Tank-Automotive Command which showed that under stable vibration conditions it provided a good measure of what human beings would tolerate. In particular, the tests indicated that an average absorbed power of 6 watts represented the limit of human tolerance. Further tests showed that under some conditions drivers were willing to tolerate vibrations corresponding to power levels of 9 or even 15 watts, for several minutes at least (13.8). Nevertheless, an absorbed power limit of 6 watts has been used to calculate the maximum sustained speed of vehicles over rough ground and the speeds calculated on the basis of it have proved to vary with the terrain roughness in a way similar to the experimental results illustrated in Fig. 13.1. Moreover, not only are the broad patterns of the calculated and observed variations of speed with terrain roughness similar but in some cases maximum speeds calculated on the basis of the 6 watt absorbed power limit have correlated fairly closely with the maximum speeds at which crews would drive vehicles (13.9). There is a good case, therefore, for using the 6 watt limit for calculating the sustained speeds of tanks over rough ground and for comparing their performance on its basis.

The criterion of absorbed power is not, however, applicable to the crossing of single, discrete obstacles. In this case tank crews experience a jolt rather than continuous vibrations and their reaction is generally related to the maximum acceleration that arises at their stations. The acceleration is most frequently recorded at the driver's position and it is observed that when they are exposed to jolts drivers are unwilling to subject themselves to vertical accelerations exceeding 2 to 3 g. As a result, a vertical acceleration of 2.5 g at the driver's seat has become fairly widely accepted as a limit for the crossing of discrete obstacles (13.10).

Taking maximum vertical acceleration as a criterion for the maximum speed with which tanks can cross discrete obstacles, a relationship can be established for any particular vehicle between its maximum speed and obstacle height. An example of such a relationship at a constant maximum acceleration of 2.5g is illustrated in Fig. 13.2, which shows clearly that the maximum speed with which discrete obstacles can be crossed decreases rapidly with their height.

13.2 Dynamics of Vehicles

The displacements and accelerations which are produced when tanks move over rough ground depend, of course, not only on their speed and the geometry of the terrain surface but also on their dynamic characteristics. A good insight into the effect of these characteristics can be gained by considering a simple, single degree of freedom model of a vehicle moving over a surface with a sinusoidal profile, which is illustrated in Fig. 13.3. As shown, the vehicle is represented by a mass m

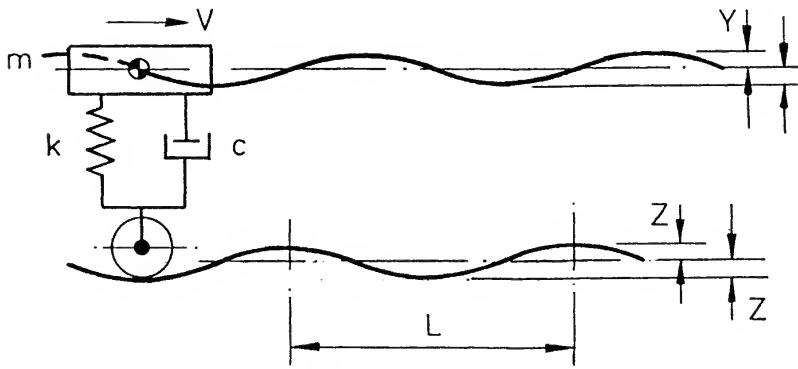


Fig. 13.3 Simple, single degree of freedom model of a vehicle moving over a sinusoidal surface.

connected by a linear spring of stiffness k and a viscous damper with a damping coefficient c to a wheel of negligible mass which follows the profile of the surface. If the vehicle is moving with a constant horizontal velocity V, the amplitude of its vertical oscillations Y is given by the following standard solution (13.11):

$$\frac{Y}{Z} = \frac{\sqrt{1 + 4\zeta^2\left(\frac{\omega}{\omega_n}\right)^2}}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\zeta\left(\frac{\omega}{\omega_n}\right)^2}} \qquad \text{.............. 13.1}$$

where
Z = amplitude of sinusoidal surface profile
ω_n = natural frequency of vehicle = $\sqrt{k/m}$
ω = forcing frequency = $2\pi V/L$
L = wavelength of sinusoidal surface
ζ = damping ratio = c/c_c
c_c = critical damping coefficient = $2\sqrt{k\,m}$

The relationship between the ratio of the amplitudes Y/Z and the ratio of the frequencies ω/ω_n given by equation 13.1 is shown graphically in Fig. 13.4, where the two ratios are plotted against each other for three different values of the damping ratio. To relate the results presented in Fig. 13.4 to the response of any given vehicle moving over a particular surface one must recognise that the amplitude ratio is proportional to the amplitude of the vertical displacement of the vehicle and the frequency ratio to its speed.

The pattern of the curves plotted in Fig. 13.4 shows clearly the need for damping to avoid large vertical displacements near resonant frequency, that is at speeds when the forcing frequency equals, or is close to, the natural frequency of the vehicle. However, Figure 13.4 also indicates that at forcing frequencies greater

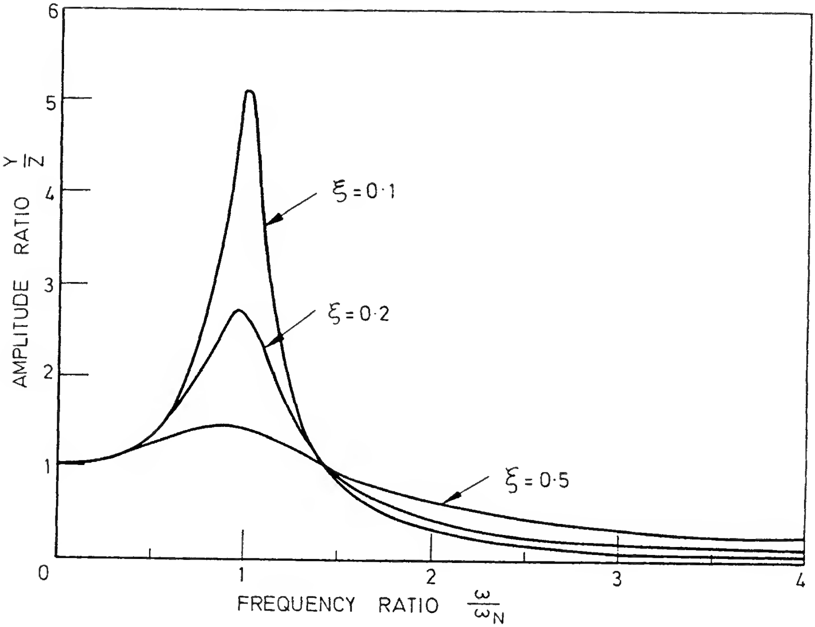


Fig. 13.4 Ratio of the amplitudes of vertical oscillations and of the surface profile versus the ratio of forcing and natural frequencies at three different values of the damping coefficient.

than the natural frequency, or more precisely at frequency ratios greater than $\sqrt{2}$, damping should be as low as possible in order to achieve low ratios of amplitudes and, therefore, small vertical displacements for any given surface profile.

The need for viscous damping to be low at frequency ratios greater than $\sqrt{2}$ is also indicated by the acceleration imparted to the vehicle. The acceleration is most conveniently described in non-dimensional terms as a ratio of its amplitude $\ddot{Y}$ to the product of the amplitude of the surface undulations Z and the natural frequency of the vehicle ω_n. This ratio can be shown to be equal to the amplitude ratio Y/Z, given by equation 13.1, multiplied by the square of the frequency ratio ω/ω_n and is shown plotted against the latter in Fig. 13.5. For any given vehicle and surface profile the quotient $\ddot{Y}/Z\omega_n$ is proportional to the vertical acceleration of the vehicle and the frequency ratio ω/ω_n is proportional to its speed, as before. In consequence, curves shown in Fig 13.5 represent the variation of the vertical acceleration with speed and they show clearly that when ω/ω_n is greater than $\sqrt{2}$ the acceleration rises rapidly with speed as damping increases. Thus, to minimise the acceleration, viscous damping should be as low as possible. Otherwise Figures 13.4 and 13.5 indicate that to reduce the displacements and accelerations of vehicles to a minimum their natural frequencies should be as low as possible, so that they operate to the greatest possible extent at speeds which are above those corresponding to $\omega/\omega_n = \sqrt{2}$. This means that the spring stiffness, or spring rate, should be low, since $\omega_n = \sqrt{k/m}$.

However, low spring rates and the low natural frequencies that go with them

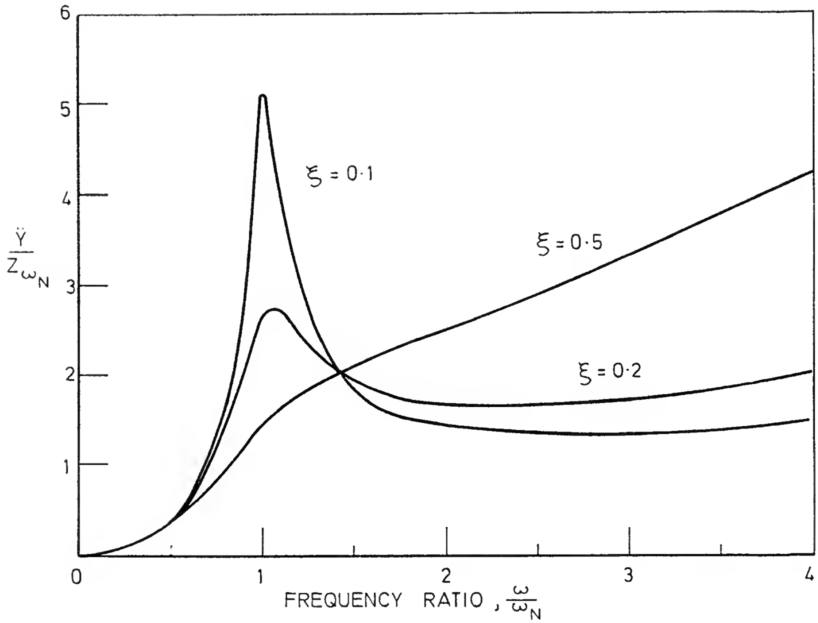


Fig. 13.5 Quotient proportional to vertical acceleration plotted against the frequency ratio, which is proportional to speed, for three different values of the damping coefficient.

result in large movements of the wheels in relation to the forces acting on them. Thus, low spring rates are only effective if they are used with suspensions which allow relatively large vertical movement of the road wheels and in particular from their position under static loads to where they hit the bump stops. Otherwise the springs cease to be operative when the forces acting on the wheels are not much higher than the static loads and the hull of the vehicle experiences high impact forces even at relatively low speeds.

The preceding comments have been confined to the vertical oscillations, or bounce, of tanks. But they also rotate, or pitch, in the vertical plane containing their longitudinal axis and this can be more important than bounce, particularly when the turret crew rather than the driver are considered. However, in principle, tanks pitch in much the same way as they bounce. They also rotate, or roll, about their longitudinal axis but roll is, in general, the least important mode of their motion.

The above discussion of the dynamics of tanks has also been confined to movement over surfaces with sinusoidal profiles. Such profiles have been used for some time for suspension test tracks (13.12, 13.13). They may also be regarded as an approximation to some terrain profiles (13.14). But terrain profiles are generally of a random nature. In consequence, attention has been given in recent years to the application of the theory of random vibrations to the movement of vehicles off the road (13.15). This has resulted in more accurate, statistical descriptions of terrain profiles but it has done little to help the understanding of the basic

problems of tank suspensions. It is also questionable whether, for all its mathematical sophistication, the theory of random vibrations is likely to be of much help in improving tank suspensions in view of the wide variety of surfaces over which tanks are expected to operate.

13.3 Early Types of Suspensions

The first and all other tanks built in Britain during the First World War had nothing between their hull frames and the tracks other than rigidly mounted rollers. This was acceptable only for operation at low speeds for which the early tanks were, in fact, designed. However, the first French tank, the Schneider, already had rollers mounted on sub-frames which were sprung by coil springs, although this represented no more than an adaptation of the arrangement devised earlier for tracked agricultural tractors.

During the 1920s and 1930s most tanks were fitted with suspensions based on pairs of rollers, or road wheels, mounted in tandem on balance beams. The latter could pivot about their centres which were sprung by leaf or coil springs, or were made resilient themselves by one half or the whole of them being formed out of leaf springs. In many cases the balance beams were not sprung individually but were connected in pairs, either by secondary balance beams, so that they rocked about a common pivot, or by a spring. The best known and probably the earliest example of this type of suspension was that introduced in 1928 on the Vickers-Armstrongs Six-Ton Tank and subsequently used in the Soviet T-26, as well as other tanks. In this case one half of the secondary balance beams consisted of leaf springs, so that they provided some springing, and the system of beams resulted in the hull of the tank being mounted on the equivalent of only two axles, even though there were eight wheels per side (13.16).

Suspensions of this kind were intended to equalise the loads between the rollers or road wheels and to adjust to the irregularities of the ground by the rotation of the beams about their pivots rather than by the deflection of the springs. The springs used in them were relatively stiff and provided only limited vertical travel to the beams and the wheels. The suspensions worked, therefore, mainly by walking beam action, which was reasonably effective at low speeds. But they were ineffective at higher speeds because their balance beams could not respond rapidly enough to the irregularities of the ground when these were traversed at any speed. In view of this they were very aptly called 'slow-motion suspensions' and because of their speed limitations they were eventually abandoned during the Second World War.

Since then the majority of tanks have been built with suspensions in which the road wheels are both mounted and sprung independently of each other. Such independent suspensions had already appeared in the late 1920s but before they were generally adopted many tanks were fitted with suspensions of yet another kind. In these the road wheels were also mounted individually on leading and trailing arms but were not sprung independently. Instead, pairs of adjoining arms were interconnected by sprung balance beams or directly by springs. This resulted in suspensions which resembled those of the balance-beam type in so far as they equalised loads between pairs of wheels but which remained effective to higher speeds, because of the lower inertia of their unsprung parts. But at high speeds they were still not as good as independent suspensions, which have the lowest unsprung masses and which provide more vertical travel for individual road wheels.

Suspensions with leading and trailing arms interconnected by a sprung balance beam are exemplified by the vertical volute spring suspensions which were widely used on US tanks, from the T5 Combat Car of 1935 to the M5 light and M4 medium tanks of 1943-44. The earliest and most widely used of the suspensions with leading and trailing arms interconnected directly by a spring has been the Horstmann suspension which was introduced in 1930 in the A.4 E.8 version of the British Mark IA light tank built by Vickers-Armstrongs. Different versions of this type of suspension were widely used during the 1930s in light tanks, including the Vickers Carden Loyds, the Soviet T-37 and T-38 and the French R-35 and H-35. Other versions of the Horstmann suspension were later developed in Britain for heavier tanks, starting in 1943 with the Centurion and then following with the 65 ton Conqueror. The version developed for the Centurion has continued to be used in the Chieftain and in the 1970s it was also retained in its derivative, the Khalid tank.

The use of independent suspensions was pioneered in the United States by J W Christie, who first demonstrated one in 1928. The original Christie independent suspension consisted of four large-diameter road wheels per side mounted on three trailing and one leading arms, each of which was connected to a long, vertical coil spring (13.17). The springs were relatively soft which meant that the natural frequency of Christie's vehicle was commendably low. Its suspension also provided the road wheels with a vertical travel of about 350mm, which was considerably greater than that of the road wheels of earlier tanks and indeed of most tanks built since. Christie's vehicle could, therefore, move over rough ground at greater speeds than other tanks.

In consequence, the independent suspension devised by Christie was adopted for several tanks, which were generally considerably faster than others of their period. They included the Soviet *Bystrochodni*, or 'fast', tanks, starting with the BT-1 of 1931, and their eventual successor, the T-34 medium tank which in its different forms continued to be produced until about 1956. They also included British cruiser tanks, from the A.13 of 1937 to the Comet of 1944. The Comet and its immediate predecessor, the Cromwell, had the most highly developed and the most successful form of the suspension originated by Christie. However, the Comet was also the last tank to be designed with this type of suspension. There were two principal reasons for this. One was the amount of hull space occupied by the springs of the Christie suspensions which were generally mounted within the hull for protection. In particular, the springs took up a significant amount of hull

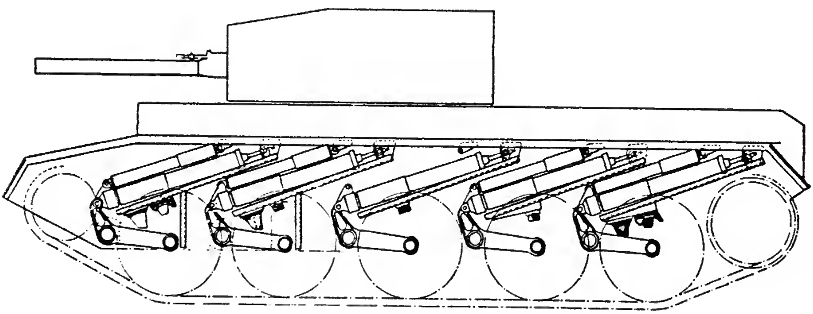


Fig. 13.6 Christie suspension of the British Cromwell tank.

width which became critical as tank turrets and their bearings grew bigger while the overall width of tanks continued to be constrained by the dimensions of the existing railway bridges, tunnels and so on. The other reason for the Christie suspension being given up was the successful development of another type of independent suspension. In this trailing or leading arms were sprung by transversely mounted torsion bars which made it simpler and lighter and did not take up any hull width.

Independent suspensions with torsion bars were first used in 1938, on Model D of the German Pz.Kpfw.II light tank and then on Model E of the Pz.Kpfw.III medium tank. At about the same time torsion bar suspensions were also incorporated in the design of the German DW-1 and Soviet T-100 and SMK experimental heavy tanks. This was followed by their adoption for all Soviet heavy and light tanks, starting with the KV-1 and the T-50, while in Germany the example of the Pz.Kpfw.III was followed in 1942 by the Tiger and then by the Panther. In the United States torsion bar suspensions were not used until 1943, when one was installed in the experimental T20E3 medium tank. However, by 1945 they were incorporated in every new US light, medium and heavy tank design. This was equally true of US tank designs after 1945, until the mid-1950s when hydropneumatic suspensions began to be considered. Almost all other tanks designed between the end of the Second World War and the 1960s have also had torsion bar suspensions, except for the British battle tanks fitted with Horstmann suspensions.

13.4 Torsion Bar Suspensions

The main reason for the widespread adoption of torsion bar suspensions has been their light weight and the high levels of performance that can be achieved with them. The light weight is due, in turn, to the basic simplicity of torsion bar suspensions and to the ability of torsion bars to store more energy in relation to their weight than other springs.

Table 13.1 **Vertical Travel of the Road Wheels of Tanks**

Tank	Suspension Type	Vertical Wheel Travel, mm		
		Bump	Rebound	Total
T-34	Christie	120	120	240
Cromwell	Christie	226	190	416
Centurion	Horstman	83/146+	89	172/235+
Chieftain	Horstman	83/159+	83	166/242+
Pz.68	Conical disc springs	206	70	276
Merkava Mark 2	Coil springs	210	85-170	295-380
Merkava Mark 3	Coil springs	300	300	600
M48	Torsion bar	206	114	320
M60A1	Torsion bar	165	127	292
AMX-30	Torsion bar	186	92	278
Leopard 1	Torsion bar	227-279	128-156	383-407
Leopard 2	Torsion bar	350	176	526
M1	Torsion bar	380	178	558
S-tank	Hydropneumatic	181-324	198-219	379-543
MBT-70	Hydropneumatic	400	200	600
Challenger	Hydropneumatic	350	100	450
Osorio	Hydropneumatic	330	70	400

+one wheel rising only

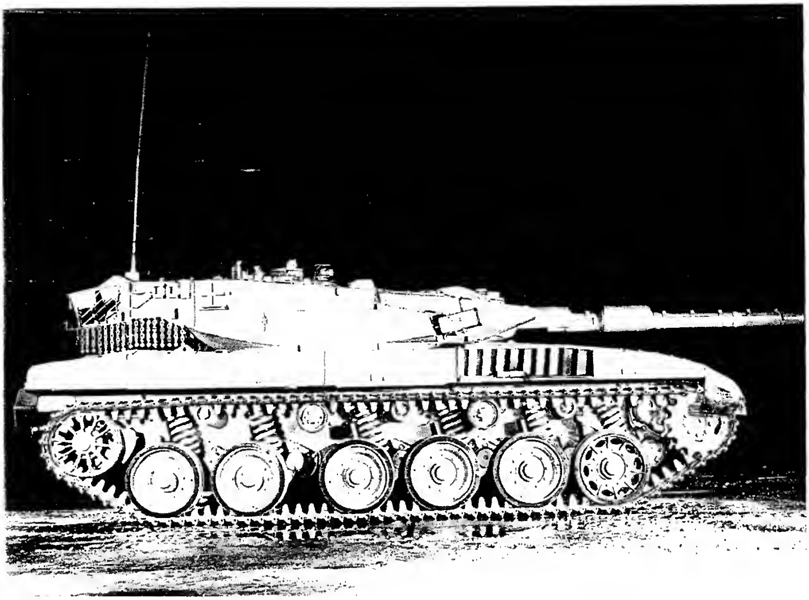


Fig. 13.7 Externally mounted, independent, coil spring suspension of the Israeli Merkava Mark 3. (IDF)

The advantages of torsion bar suspensions are however accompanied by a number of disadvantages. Thus, while the installation of the torsion bars across the bottom of tank hulls is simple and well-protected, it also increases their height. This is undesirable in itself and it can also significantly increase the weight of tanks, particularly when they are heavily armoured. Damaged torsion bars are also difficult to replace when a hull is distorted by mine blast. Moreover, the fact that torsion bars store a large amount of energy in relation to their weight means that their outside is highly stressed, which makes them vulnerable to surface damage.

Their installation in the hull makes torsion bar suspensions compare unfavourably in some respects with suspensions of the Horstmann type. In the case of the latter the coil springs are outside the hull, mounted together with their associated pairs of wheels and suspension arms on a subframe so that they form a self-contained bogie which can be replaced as a unit in the event of damage. The same applies to the externally mounted suspension of the Israeli Merkava. The latter is however greatly superior to the Horstmann suspension of the British Centurions and Chieftains because the road wheels are independently sprung, by vertical coil springs, and because they are provided by it with greater vertical travel.

Another and in fact the first battle tank to be produced with an externally mounted independent suspension has been the Swiss Pz.61, which also has a unique type of springs consisting of stacks of conical discs or Belleville washers. This form of springing first attracted attention in Germany during the latter part of the Second World War because of its relatively high energy storage capabilities and it was to be incorporated in the externally mounted suspension which was being

developed for the E series of tanks (13.18). None of the E tanks was completed when the war ended but the idea of using conical disc springs was revived in the 1950s in Switzerland and they were incorporated in the suspensions of the Pz.61 and then of the Pz.68.

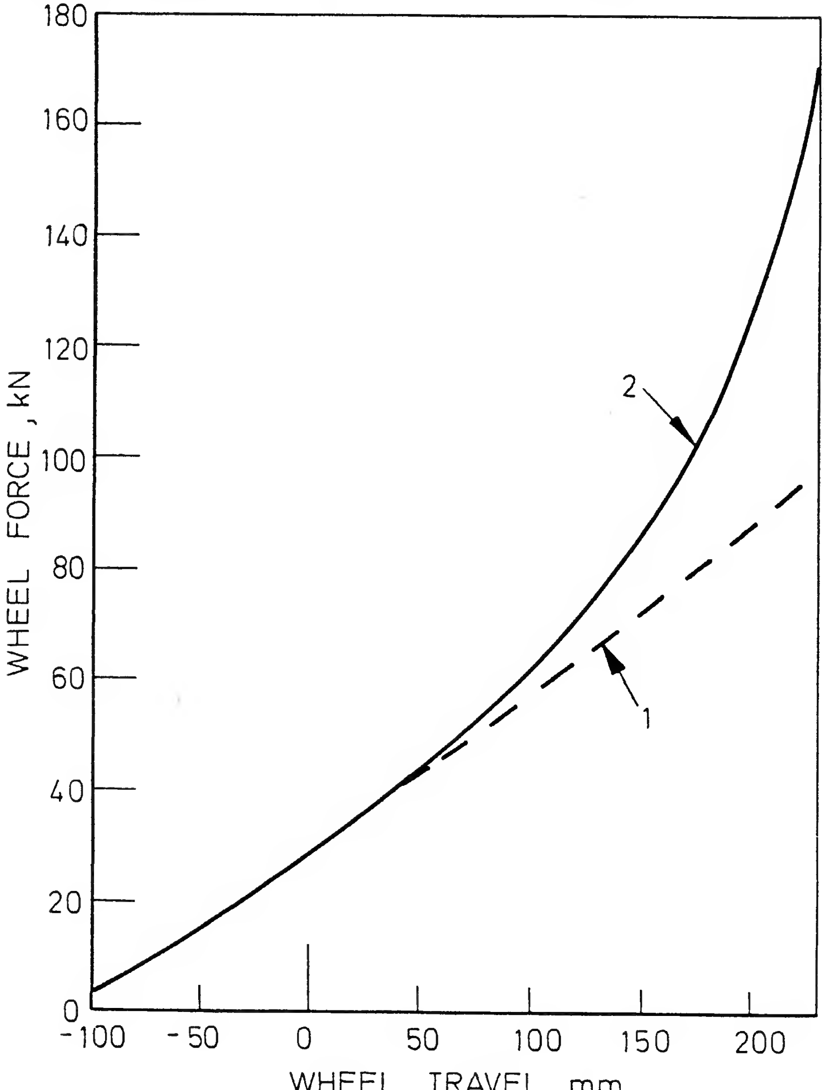


Fig. 13.8 Force versus wheel travel from the static laden position for a typical vehicle with a simple torsion bar spring system (1) and with an auxiliary spring giving rise load-deflection characteristics (2).

The vertical movement which the different suspensions provide for the road wheels is generally considered in two parts. The first and by far the more important of the two is called 'bump' or 'jounce' and covers the travel of the wheels from the static laden position, when the springs are only acted on by the weight of the sprung mass of the vehicle, to the upper limit of their travel, usually set by bump stops on the hull. The second part, called 'rebound', covers wheel travel from the static laden position to the lower limit of travel, when there is no load on the wheel or when the wheel is arrested short of this by suspension stops or the track.

The bump and rebound travel provided by a number of typical suspensions is listed in Table 13.1, which indicates that bump may be no greater than rebound but that more generally it is two to four times the latter. If the load-deflection characteristics of the suspensions were linear and rebound travel were equal to the static deflection. Table 13.1 would also suggest that tank suspensions are designed so that the road wheels do not come up to the limit of their bump travel until the forces acting on them are equal to between two and five times the static load. In fact, only simple suspensions with metallic springs have load-deflection characteristics which are approximately linear and in most cases rebound is restricted to less than the static deflection. Nevertheless forces on the wheels at full bump range from two to five or, in the extreme, six times the static load.

The greater the ratio of the force at full bump to the static load the less likely, or frequent, is the incidence of the bump stops being hit and therefore of large impact forces being transmitted to the hull. In consequence, the greater the ratio the more severe are the obstacles which can be negotiated at speed. However, short of the extreme conditions which cause the bump stops to be hit, the principal suspension requirement is for relatively soft springs and this generally implies large bump travel. Thus, the best suspensions are those which provide not only a high ratio of the force at full bump to the static load but also large bump travel. The two go together, of course, in the case of suspensions with linear load-deflection characteristics and wheel travel has been used therefore as a single measure of the ability of tanks to negotiate obstacles at speed. In fact, it has been related directly to the height of the obstacles over which tracked vehicles can ride at maximum speed. For instance. bump travel of approximately 180mm has been put forward as necessary to ride over obstacles up to 130mm high, 330mm for obstacles of up to 250mm, and so on (13.19).

Because wheel travel is usually related to spring stiffness, large values of it are also associated with low natural frequencies, which are desirable for the reasons indicated earlier. Some tanks built during the Second World War still had a bounce natural frequency of more than 2 or even 3Hz. But others, with softer springs, already had a bounce frequency of about 1Hz and this has not been improved upon since then, most tanks produced in recent years having a bounce frequency of between 1 and 1.5Hz. In all cases pitch natural frequency has been lower, being equal to between 0.55 and 0.7 of the bounce frequency.

To achieve low natural frequencies and large wheel travel a considerable amount of effort has been devoted to improving the springs used in tank suspensions. In particular, since the emergence of the general trend towards the use of independent suspensions with torsion bars, much of this effort has been directed at the improvement of torsion bar springs. The basic problem with them has been that their performance depends on how much they can be twisted and that this is constrained by two factors. One is their length which, because of their transverse location, is limited in the case of simple torsion bar springs to the width of tank hull. In consequence the length of torsion springs can only be increased by using

either two bars or a bar within a torsion tube, the two working in series in each case.

The first solution was adopted in 1942 in the German Panther tanks, which had two torsion bars mounted in parallel, the second bar being connected to the end of the first by a short balance beam and anchored at its other end to the hull wall. As a result, the total length of each spring unit was doubled, although at the cost of imposing some bending in addition to torsion on the bars.

The other solution attracted a considerable amount of attention in the 1960s in the United States and led to the development of spring units consisting of a torsion bar within a torsion tube. In this case the outer ends of the bar and of the tube were connected by a spline coupling and the spring unit was anchored to the hull at the inner end of the tube. The tube over bar arrangement again allowed the total length of the unit to be, virtually, twice that of a simple torsion bar spring and, therefore, provided more angular deflection and wheel travel. The tube also made more efficient use of spring material than the bar, because more of it could be highly stressed, and it protected the vulnerable outer skin of the bar from damage. Moreover, the tube over bar spring is unaffected by any twisting of the hull, because the bearing supporting it and its anchorage are on the same side of the hull, close to each other. This also makes it easier to withdraw the spring in the event of damage. However, tubes are more expensive to manufacture than bars and tube over bar springs have not been adopted for tanks. But they have come into use on at least two other tracked armoured vehicles, namely the LVTP7 amphibious carrier and the Armoured Infantry Fighting Vehicle produced by the FMC Corporation.

Instead, the development of torsion bar suspensions has concentrated since the early 1970s on the use of single torsion bars of higher strength steels. These have allowed higher stresses to be imposed on the bars and, therefore, greater degrees of twist and more wheel travel for any given length of bar. Thus, during the Second World War torsion bar suspensions were still being designed to have a maximum shear stress of not more than about 300 MN/m^2 (13.20). But improvements in the manufacture of spring steels and of torsion bars resulted in a maximum shear stress of about 800 MN/m^2 becoming the norm during the 1950s. The torsion bars of the US M41 light tank of that period, which were made of SAE 8660 steel and were surfaced worked, could be operated already at stresses of up to 930 MN/m^2 (13.21). Further progress allowed the maximum shear stress to be raised to 1100 MN/m^2, at which level torsion bars of high strength steel could withstand 80 000 cycles of loading. In the case of the US M113A1 armoured carrier this made it possible to increase the bump travel from 150 to 230mm (13.22).

Advances in metallurgical techniques and in particular in vacuum arc remelting and in electroslag remelting of steels raised the maximum shear stress still further. Thus, torsion bars of SAE 4350 H steel have been able to operate at up to 1240 MN/m^2 for 68 000 cycles of loading. As a result of these developments the bump travel of torsion bar sprung road wheels of tanks developed during the 1970s, such as the German Leopard 2 and the US M1, increased to 350 and 380mm, respectively, compared with 200mm which was typical of suspensions developed during the previous two decades.

Attempts have also been made to use materials other than steel for the torsion bars and in particular to make them out of titanium. At least one vehicle, the XM800 Armored Reconnaissance Scout Vehicle built in the early 1970s by FMC Corporation, had titanium torsion bars. But, in spite of its lower density, titanium has not proved superior to high strength steels as a spring material.

In addition to being made of progressively stronger steels, torsion bars have been supplemented by the fitting of auxiliary springs which come into play as the road wheels approach the end of their bump travel. Initially most auxiliary springs have been of the volute type and their addition to the primary, torsion bar springs produced suspensions which become considerably stiffer towards the upper end of the wheel travel. Suspensions with such rising load-deflection characteristics offer the advantage of a relatively low natural frequency near their normal, static deflected position and, at the same time, prevent the road wheels from hitting the bump stops when the impact forces are relatively low.

More recently the volute springs have been replaced on tanks such as the German Leopard 2 and the Israeli Merkava Mark 2 and 3 by hydraulic bump stops. In the case of the Leopard 2 they come into action over the last 38 per cent of bump travel and provide resistance to wheel travel rising to 3.5 times the static wheel load (13.23).

13.5 Damping

Because resonance can result in large oscillations, suspensions need to be well damped, as already indicated. On the other hand, damping should be as low as possible to minimise the transmission of impact forces, especially at high speeds or, what amounts to much the same thing, at high forcing frequencies. In consequence, the amount of damping that is provided is generally a compromise between controlling resonance and minimising the transmission of forces at high frequencies. This leads to damping ratios of the order of 0.2 to 0.4 with the hydraulic dampers which are commonly used.

To enable somewhat higher damping ratios to be used relief valves have come to be incorporated in hydraulic dampers to limit the magnitude of the forces generated in them. Thus, damping is made to increase, as required, with road wheel velocity but only up to a velocity at which the relief valve blows-off. After this there is almost no further increase in the damping force, which at blow-off is typically equal to 1.5 times the static wheel load.

In most cases dampers have been fitted only to the front and rear road wheels. The reason for not fitting them to the centre wheels is that they are ineffective there in damping pitching resonance, which sets in at lower frequencies than bounce resonance and is generally more disturbing. In fact, bounce resonance not only sets in later than pitch resonance but does so at frequencies beyond the cross-country speed of many vehicles. However, damping of the vertical oscillations becomes important at high speeds. In consequence, there has been a tendency to fit dampers to an increasing proportion of the road wheels and the British Cromwell tanks of 1944 already had dampers fitted to all but the centre of the five road wheels on each side.

Although the dampers which are generally fitted are commonly regarded as being of the viscous type damping in them is not actually achieved by viscous forces but by the resistance to the flow of hydraulic fluid through orifices whose opening is controlled by spring-loaded valves. Nevertheless, damping produced by them is still proportional to the relative velocity between the road wheels and the hull.

Most of the hydraulic dampers have been of the direct-acting, telescopic type but lever-operated, double-piston and rotary, vane-type hydraulic dampers have also been used. The last two have an advantage over the direct-acting telescopic dampers in having relatively large areas of contact with the hull side plates to

which they are directly bolted. This provides a good conductive path that helps to dissipate the heat generated within dampers, which can be considerable and which can reduce their effectiveness. In contrast, the heat generated within telescopic dampers has to be dissipated entirely to the surrounding air. On the other hand, telescopic dampers allow greater piston travel, which results in lower operating pressures and less severe sealing problems.

A considerable amount of friction was inherent in the leaf springs of the early tank suspensions and it provided the only form of damping which was present at first. Friction dampers have also been used, their principal attraction being greater durability than that of hydraulic dampers. On the other hand, friction damping has been less consistent and has not provided as good a range of characteristics as hydraulic damping. Nevertheless, highly-developed, disc-type, rotary friction dampers have been adopted for the Leopard 2 tank.

Other attempts to improve on the characteristics of the hydraulic dampers have led to systems which provide frequency dependent damping. In its simplest form this involves the addition of a spring in series with the damper, which produces what is sometimes known as relaxation damping. More elaborate attempts involve varying the damping coefficient by means of a control system which senses the acceleration of the hull and the velocity of the wheels relative to it. As a result, damping can be varied to better meet the conflicting requirements of resonance control and low force transmission at high frequencies.

13.6 Hydropneumatic Suspensions

The desired characteristic of a low natural frequency can be achieved over much of the operating range of the suspension without incurring the disadvantages associated with very low rate metallic springs by using, instead, hydropneumatic spring units. These contain a volume of gas separated by a floating piston, or a diaphragm, from the hydraulic fluid which transmits pressure between it and a second piston connected to the road wheel arm.

Because their resilience is based on the compressibility of the gas, hydropneumatic spring units have highly non-linear load-deflection characteristics. This makes it possible to obtain a low natural frequency when the road wheels are operating around their static position. At the same time it also provides a spring rate which rises rapidly as the road wheels approach the limit of their bump travel and thereby prevents the suspension arms from being forced against the bump stops by relatively small impacts, as would otherwise be the case.

As a result, the natural bounce frequency of tanks with hydropneumatic suspensions is significantly lower than with metallic spring systems, a typical value being about 0.7 Hz. The wheel travel provided by them is also as large as with the best of the metallic spring systems, typical values being given in Table 13.1.

Other advantages of hydropneumatic suspensions include their spring units being self-contained and normally bolted to the outside of hull side plates. This means that they do not add to the height of hulls, as torsion bars do, and that they need not take up any space within the armour envelope. In consequence, the use of hydropneumatic suspensions can produce significant savings in the weight of tanks.

Because they are self-contained, hydropneumatic suspension units are simpler to install than the separate springs and dampers of other types of suspensions. Also, because each unit is a damper as well as a spring, they provide better damping, overall, than suspensions in which dampers are only fitted to some of the

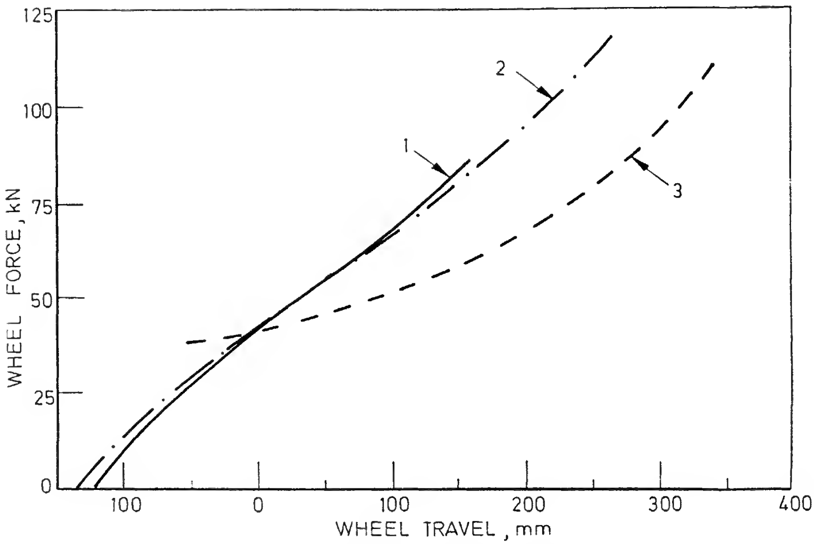


Fig. 13.9 Wheel force versus wheel travel of three different spring systems:
1 = standard torsion bar system
2 = high strength torsion bar system
3 = hydropneumatic spring system

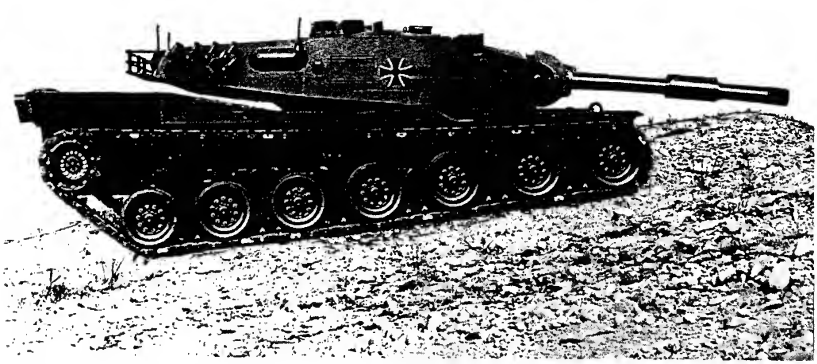


Fig. 13.10 MBT-70 pitched forward by means of its adjustable hydropneumatic suspension to gain additional depression for its gun on a reverse slope.

road wheels. Moreover, when they are bolted to the hull they can better dissipate the heat generated by damping than telescopic dampers because the hull constitutes a large heat sink.

By connecting their units hydraulically to a control system hydropneumatic suspensions can be made to offer further advantages, although at some cost in terms of complication and space within the hull. In particular, when hydropneumatic suspension units are connected to a control system hydraulic fluid can be pumped into or out of them to raise or to lower the hull, thereby increasing or decreasing the ground clearance and the overall height of the tank. What is more, the fluid can be transferred from units at one end of a tank to those at the other end to change the pitch of its hull. This is particularly important because it enables tanks to depress their guns to a greater extent and, therefore, helps them take up firing positions on reverse slopes behind the cover of hill crests. The ability to alter the pitch of the hull also reduces the depression which has to be provided to guns within tank turrets and consequently makes it possible to reduce the overall height of tanks.

Although they had already been introduced in motor cars, hydropneumatic suspensions only began to be considered for tanks during the mid-1950s. Their earliest installations were in the Rheinstahl-Hanomag prototype of the German Leopard 1 tank and in the prototypes of the Swedish S-tank, both of which were designed during 1958-1960. At about the same time work on hydropneumatic suspensions also began in the United States, leading to the installation of one in the US T95 medium tank, which was originally designed with a torsion bar suspension. Subsequently another hydropneumatic suspension was incorporated from the start in the design of the US-German MBT-70. However, only one of the early hydropneumatic suspensions was developed to the stage of being put into production. This was the suspension developed by Bofors for the S-tank, which entered service with the Swedish Army in 1967.

The use of hydropneumatic suspension in the S-tank was favoured, or even made essential, by the whole concept of its design which was based on the use of a gun fixed in the hull. In consequence, the gun of the S-tank has had to be elevated and depressed by changing the pitch of the hull and the most convenient way of doing this was by means of an adjustable hydropneumatic suspension. Thus, a hydropneumatic suspension system was adopted for the S-tank which enabled hydraulic fluid to be transferred between the front and rear suspension units, by an elevation pump located between each pair of diagonally connected units, to raise the front and lower the rear wheels or vice versa. This produces the required variation in the pitch of the hull and, therefore, in the elevation of the gun, from +12 to −10 degrees. The hydraulic interconnection between the front and rear units is also arranged to lock-out the suspension whenever the gun firing button is pressed, which makes the S-tank much more stable as a gun platform. All this is done without any hydraulic connections to the suspension units for the two centre wheels on each side which are independent of each other and of the rest of the system.

The first turreted tank with a hydropneumatic suspension did not come into service until eight years after the S-tank. The tank was the Japanese Type 74, which was developed by Mitsubishi Heavy Industries between 1961 and 1968. Its suspension units were again interconnected and used to vary the pitch of the hull as well as the ground clearance. The pitch varies between +5.5 and −6 degrees and advantage has been taken of this to reduce the amount of depression provided by the gun mounting to −6.5 degrees and consequently to reduce the height of the

turret. Yet the gun of the Type 74 tank has a total depression of −12.5 degrees over its front, which is more than the customary maximum of −10 degrees and a significant advantage from the point of view of firing from reverse slopes.

A similar advantage of a lower turret height is enjoyed by the South Korean Type 88 tank, the gun of which has a depression of −6 degrees but this can be increased to −10 degrees by altering the pitch of the hull by means of the adjustable hydropneumatic units of its hybrid suspension. The latter consists of a combination of hydropneumatic units at the first and the last two road wheels on each side and of torsion bars at the remaining three centre wheels. This type of hybrid suspension was first incorporated in the General Motors design of the US XM-1 tank and has the advantage of exploiting the light weight of torsion bar springs but it complicates the shape of the hull sides and the torsion bars take up height in the centre of the hull where this is most objectionable.

The hydropneumatic units which form the basis of the suspensions of the S-tank and of the Type 74 are of the single-cylinder linear type and are mounted within the hull. However, other hydropneumatic units have been mounted externally and several early experimental units have been of the two-piston type, with two opposed cylinders. The latter include the units made in Germany by Friesecke & Hopfner during the mid-1960s for the MBT-70 and others, developed since the late 1970s by Messier and by SAMM as part of the French AMX Leclerc tank programme. But although they provide a degree of redundancy, units of the two-piston type with opposed cylinders have been abandoned in favour of the simpler single-piston, single-cylinder units, which are exemplified by those developed by Laser Engineering for the British Challenger and by Dunlop for the Engesa Osorio tanks.

To reduce their length, several units have been produced with a separate actuator cylinder containing the piston connected to the road wheel arm and an accumulator cylinder containing the nitrogen gas working medium, the two cylinders being arranged in parallel with the hydraulic fluid flowing between them through a damping manifold. Units of this kind appear to have been developed originally in the United States by the National Water Lift Company for the MBT-70 in a four-cylinder, two-piston configuration and then in the two-cylinder, single-piston form for the US XM-803 and the General Motors XM-1 prototype. Others of the latter type were produced subsequently by Teledyne Continental Motors for the modernised Centurions of the Jordanian Army and for the South Korean Type 88.

The most recent type of unit to be developed is also of the two-cylinder, single piston type but with the cylinders incorporated in the road wheel arm, like the conical disc spring units and dampers of the Swiss Pz.61 and Pz.68 tanks. The in-arm type of hydropneumatic suspension unit offers the advantage of further savings in space, although it increases somewhat the unsprung mass of the vehicle and makes it more difficult to interconnect units hydraulically, if this is wanted. It has attracted increasing attention since the first was developed in the United States in the mid-1970s by the National Water Lift Company and tested in a MICV test bed. Several other in-arm units have been developed during the 1980s, including Model 2880 designed by Teledyne Continental Motors and the 14K ISU developed by Cadillac Gage Textron for the US M1 tank. The 14K ISU is unusual in dispensing with the customary separator piston between the nitrogen gas and the hydraulic fluid and in having a hydraulic pressure actuated multi-plate wet friction damper.

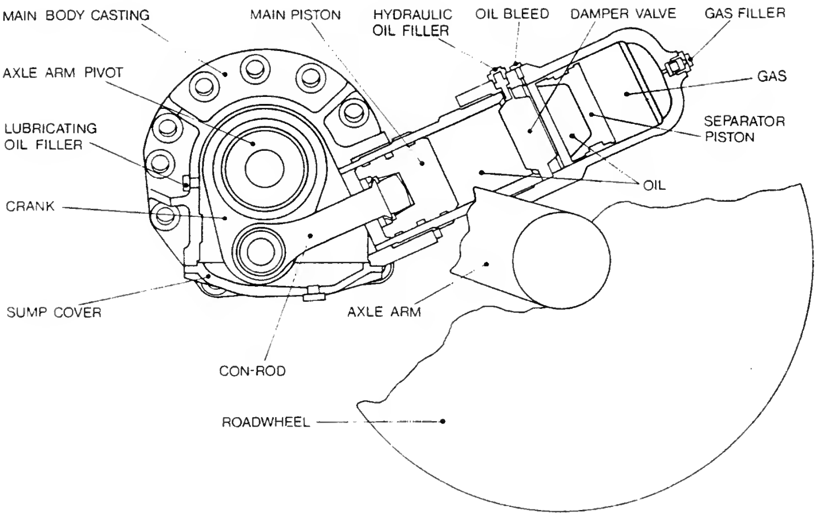


Fig. 13.11 Hydropneumatic spring unit of the type fitted to the British Challenger tank. (Air-Log)

Fig. 13.12 Chrysler prototype of the US XM-1 tank retrofitted with the Cadillac Gage in-arm hydropneumatic suspension moving at speed over a bump. (Cadillac Gage Textron)

13.7 Active Suspensions

Apart from its more immediate results, the development of hydropneumatic suspensions has opened the possibility of providing tanks with active suspension systems. Such systems embody sensors and control units as well as a hydraulic power source and they can automatically alter the characteristics of suspensions to match more closely the speed of vehicles and the terrain profile. In their ultimate form active suspensions would sense the profile of the terrain ahead of the tank and use the signals from the sensor to raise or lower the road wheels in advance of their contact with the irregularities of the ground surface in order to minimise the disturbances to the sprung mass of the tank.

Active suspensions of this kind began to be considered in the United States in the early 1960s (13.24). So far however none has been successfully developed, principally for lack of suitable terrain sensors. Radar, ultrasonic and laser as well as mechanical devices have been proposed to sense the terrain profile but a practical means of doing this still has to be developed.

A very rough degree of advance information about the ground can be provided, of course, by the driver and he could raise the front of a tank with a powered suspension on seeing the approach of a large obstacle. However, this falls well short of what could be achieved with automatic suspension control. Moreover, what the drivers can see already limits the speed of tanks in many cases. In particular, when drivers can not see possible obstacles sufficiently well ahead, because they are obscured by vegetation or for other reasons, they drive so that they can brake within the range of their vision of the ground and this can restrict the speed of tanks much more than their suspension characteristics.

13.8 Road Wheels

The design of the road wheels of tanks involves a number of conflicting factors, particularly when it comes to their size. One of them is that rolling resistance decreases with wheel diameter. This indicates that road wheels should be as large as possible, although there is some evidence that there is little to be gained by using wheels with a diameter of more than 800mm (13.25). Wheels of large diameter are also less likely to become clogged by mud, snow and stones and, as the number of wheels per tank is inversely proportional to their diameter, they make the suspension simpler and lighter. On the other hand, small diameter wheels allow more of them to be used, which spreads the weight of tanks more evenly over the length of their tracks. This reduces the peaks of pressure exerted by the tracks on the ground and, consequently, track sinkage in soft ground and it also reduces the average load per road wheel. Large diameters of the road wheels can also restrict their bump travel.

As a result, the diameter of the road wheels has had to be a compromise, which has led to it ranging from about 600 to 800mm and to tanks having five to seven road wheels per side. Some increase in the number of road wheels was achieved without sacrificing their diameter in the design of the German Panther and Tiger tanks, which followed the example of the half-track artillery tractors developed in Germany during the early 1930s in using overlapping road wheels. Thus, both were able to have eight road wheels per side, even though their diameter was 800mm in the case of Tiger I and 860mm in the case of the Panther, while Tiger II had nine wheels with a diameter of 787mm. However, the overlapping and interleaved road wheels of the Panther and Tiger I were prone to pack with mud and

snow. They were also more difficult to replace than others because the removal of one road wheel also involved others. An improvement in both respects was achieved in Tiger II the overlapping road wheels of which were not interleaved but merely staggered, although this imposed transverse bending loads on the track links.

Originally the number of wheels was considerably greater than eight or nine but their diameter was correspondingly small. In fact, early tanks such as the Anglo-American Mark VIII of 1918 had as many as 29 rollers per side and as late as 1945 Churchill tanks were being built in Britain with eleven 250mm diameter, all-steel rollers per side.

However, in 1919 J W Christie had already built an experimental tank with rubber-tyred wheels (13.26). In the mid-1920s such wheels began to be generally used and they have since become almost universal, helping to reduce track wear, noise and vibrations. But rubber-tyred wheels can not be loaded as heavily as steel-rimmed wheels of the same size. Because steel rims can be narrower than rubber tyres as well as being harder they are claimed to be better for cracking ice and packed snow off the tracks and also for squeezing through mud on the tracks, thereby reducing the risk of track throwing. This has led to the development of road wheels which have steel rims like the original steel rollers but which also have some resilience because they incorporate a ring of rubber between their rims and hubs. In consequence they are somewhat less objectionable than the all-steel wheels or rollers.

Steel tyred but resilient road wheels were introduced on the Soviet KV heavy tank in 1940 and were subsequently adopted in a modified form on the German Tiger II, as well as being used for a time on some Soviet T-34 tanks. They were to be used also on the E-series of tanks designed in Germany towards the end of the Second World War and after the war they were incorporated in the design of the British Conqueror heavy tank as well as some more Soviet tanks.

Attempts have also been made to use road wheels with pneumatic tyres. The first was inspired by J W Christie's development of tanks that could run on their road wheels without tracks, as well as on tracks, and consisted of the US Converti-

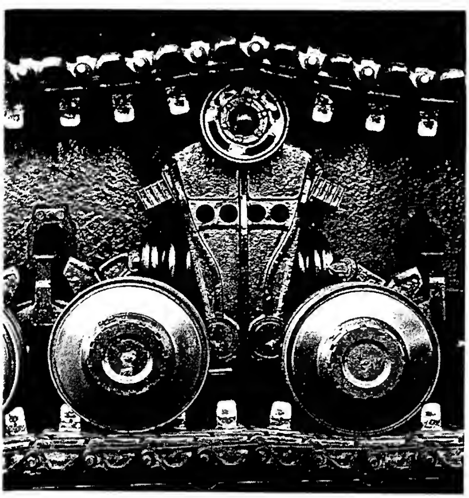


Fig. 13.13 Steel-tyred resilient road wheels of the British Conqueror heavy tank.

Table 13.3 **Characteristics of Tracks** TABLA RUEDAS P332

Vehicle	**Track**	**Track Type**	**Pads**	**Width mm**	**Pitch mm**	**Mass/m kg/m**
T-34		Dry-pin	None	550	167-170	–
Cromwell		Dry-pin	None	394	111.5	92
Panther		Dry-pin	None	660	150	162
Centurion		Dry-pin	None	609.6	140	132.5
Chieftain		Dry-pin	Replaceable	609.6	157	167.2
Challenger		Dry-pin	Replaceable	650	165	176.7
M60A1	T97E2	Double-pin	Bonded	711	176	158
M60A1	T142	Double-pin	Replaceable	711	176	194
Leopard 1	Diehl 640A	Double-pin	Replaceable	548	160	155
Leopard 2	Diehl 570F	Double-pin	Replaceable	635	183.5	181
M113	T130	Single-pin	Replaceable	381	152	64
M113	Diehl 213	Double-pin	Replaceable	379	148.5	63
Scorpion		Single-pin	Replaceable	425.5	116.3	39.7
M551	T138	Single-pin	Bonded	444.5	119.4	68.5
M41	T91E3	Single-pin	Replaceable	533	152	122

ble Combat Car T7, of 1938, which had three pneumatically tyred road wheels on each side. Another and much more questionable attempt was made in the early 1950s in France where the prototype of a 40ton Lorraine tank was fitted on each side with five road wheels with 34×7 Veil Picard pneumatic tyres (13.27). Road wheels with pneumatic tyres were also tried during the 1950s in France and in the United States on some light armoured vehicles but they have not been adopted for tanks because of their obvious vulnerability, just as the resilient road wheels with steel rims have not been generally adopted because of the track wear, noise and vibrations associated with them.

Thus, almost all tanks have come to be fitted with road wheels with solid rubber tyres and the development of the road wheels has been very largely concerned with the tyres, which are their most critical component. As part of this a variety of tyre width and thickness combinations as well as rubber compounds have been tried but only a few broad conclusions have emerged out of it all. In particular, experience with wide tyres and especially with the 230mm wide tyres of the road wheels used in most US medium tanks during the Second World War led to the conclusion that tyre width should not exceed 180mm and that dual wheels should be used if a greater width was required to spread the load (13.28). In fact, all US medium tanks built since the Second World War have had dual road wheels with a tyre width of 152mm and this has been, in general, the maximum width of tank tyres, while the use of single road wheels has become confined to a few of the lighter vehicles, such as the French AMX-10 and the Soviet BMP.

Experience with solid rubber tyres also led to the conclusion that they should be relatively thin to minimise the heating of the rubber, which occurs under cyclic loading due to hysteresis losses, and consequently to reduce the risk of tyre blow-out. As a result, the road wheels of US medium tanks have had tyres 41mm thick and the somewhat smaller road wheels of light tanks have had tyres 34mm thick (13.29). Thicker tyres would be preferable from the point of view of reducing the transmission of impact forces between the road wheels and the tracks but they would be more likely to overheat. To reduce the transmission of forces it would

also be better to use tyres of a softer rubber than that generally used but the life of such tyres would be shorter than that of tyres of the hard rubber.

The severity of loading imposed on the road wheel tyres is often expressed in terms of the average static load per unit of tyre width. But this implies line contact between the tyres and the tracks whereas actual contact is spread over areas which depend on the diameter of the wheels as well as the width of the tyres. In consquence, comparisons based on the load per unit width are only valid when the road wheels are of approximately the same diameter. Thus, it is valid to compare the loads of 99 kN/m of the US M113A1 or of 89 kN/m of the M2 IFV, both of which have road wheels with a diameter of 610mm, with 133 kN/m of the US M60A1 tank, which has 660mm diameter road wheels, and even more with the 125 kN/m of the M1 tank, which has road wheels with a diameter of 635mm. Loads of this order are representative of battle tank road wheels with a diameter of about 650mm and they also indicate that they are inevitably higher than those imposed on the tyres of lighter armoured vehicles.

Larger diameter road wheels allow higher loads per unit of tyre width. In fact, studies carried out in the United States led to the conclusion that the load carrying capacity of solid rubber tyres is proportional to the diameter of the road wheel to the power of 2.25 (13.30). The marked dependence of the load carrying capacity of tyres on wheel diameter is borne out by the loads successfully carried by the larger diameter road wheels. For instance, 800mm diameter road wheels have been operating satisfactorily at a load of 180 kN/m in the case of the Centurion and even better at 200 kN/m in the case of the S-tank, because its tracks have a smoother inner surface than those of the Centurion. Tyres of lighter tanks such as the Soviet T-54 which has road wheels with a similar, 810mm diameter are less heavily loaded at 113 kN/m and this has a beneficial effect on the durability of the tyres.

The durability of the tyres is an important aspect of the operation of tanks because it very largely governs the effective life of the road wheels. The latter tends to receive less attention than the life of the tracks but it is of considerable importance, particularly as the replacement of the road wheels in the field can be more of a problem than the replacement of the tracks.

In addition to the effort devoted to the development of tyres a considerable amount of work has been done on the structure of the road wheels. Most have come to consist of a steel disc with a welded-on rim on to which the tyre is bonded. However, in order to reduce the unsprung mass and the weight of tanks in general, aluminium alloy wheels began to be developed during the 1950s. As a result, forged aluminium alloy wheels were adopted for the US M60 and the French AMX-30 and subsequently for the British Challenger.

The adoption of aluminium alloy instead of steel wheels has produced significant savings in weight but it has made the construction of the road wheels more complicated because of the low hardness of aluminium alloys and the consequent need to protect the areas of wheels made of them which come into contact with the track guides against rapid wear. This need has been met by incorporating steel wear rings in the construction of aluminium alloy wheels or, more recently, by sprayed steel alloy wear strips.

Magnesium alloy road wheels have also been tried, particularly on very light vehicles such as the experimental ELC built in France during the early 1960s. Contemporary interest in reinforced plastics also led to trials of epoxy-bonded glass-fibre road wheels in the United States. Their weight was only one half of that of the corresponding steel wheels but their use did not advance beyond trials

because of various difficulties encountered with them, including vulnerability to local damage which is attributable to the inherently low surface hardness of reinforced plastics (13.31).

In addition to transferring the weight of the vehicle on to its tracks, road wheels have also been used in many cases to support the return run of the track, which in that case rests on the tops of them. The use of the road wheels for this purpose was pioneered in the 1920s by J W Christie and has been a common concomitant of their large diameter, although in some cases the latter has been only 580mm.

The use of the road wheels instead of separate rollers to support the return run of the tracks saves weight and helps to reduce rolling resistance. However, the use of separate return rollers makes it easier to provide large road wheel travel and to avoid either excessive sag of the upper run of the track, which can lead to the track being thrown off, or excessive track tension, which increases rolling resistance.

13.9 Tracks

Tank tracks have to perform two basic functions. One of them is to spread the load acting on the road wheels over an area of the ground sufficiently large to prevent tanks sinking unduly into it when it is soft and, therefore, to make it possible for tanks to move over it. The other function of the tracks is to transmit to the ground the tractive effort generated by the engines of tanks in order to create sufficient thrust to propel them against the resistance to their motion.

In almost all cases tank tracks have consisted of pin-jointed links, the exceptions to this being provided by a few light vehicles with continuous band tracks. The original tracks resembled those of agricultural tractors which preceded tanks. Thus, they consisted of pin-jointed steel chains with sole plates riveted on to the chain links, the upper surface of which provided a path for the flanged suspension rollers. Built up tracks of this kind were still used after the First World War on the early versions of the Vickers Medium tanks. They were then superseded by tracks with similar links but with recessed outer faces and made as one-piece nickel-chrome steel stampings. Tracks of this kind were still used on the British Matilda infantry tanks of the late 1930s and vestiges of their design survived in the form of

Table 13.2 **Characteristics of Road Wheels** TABLA TRACKS EN P331

Vehicle	Vehicle Mass kg	No. of Wheels	Wheel diameter mm	Tyre width mm	Average load per unit width kN/m
T-34	26300	10 x 2	825	150	86
Cromwell IV	27940	10 x 2	803	127	108
Panther	46500	16 x 2	860	100	142.5
Centurion	51300	12 x 2	802	116.8	179.5
Chieftain 5	55000	12 x 2	813	127	177
Challenger	62000	12 x 2	800	152	166.7
S-tank	39000	8 x 2	802	116.8	204.7
M60A1	49715	12 x 2	660	152.4	133.3
M1	53974	14 x 2	635	152.4	124
Leopard 1	42400	14 x 2	650	112	132.6
Leopard 2	55150	14 x 2	700	120	161
M113A1	10923	10 x 2	610	54	99.2
M551	16266	10 x 2	711	71	112.3
M2 IFV	22285	12 x 2	610	102	89.3
T-54	36000	10 x 2	810	156	113.2
BMP-1	13000	12 x 1	600	134	79.3

the cast, box-section track links used in the early 1940s on the British Churchill infantry tanks.

The first major advance on the original type of track was made in 1919 by J W Christie. His track consisted of plate links with multiple lugs for the connecting pins, the links being made from steel by die-stamping. Alternate links had a large horn which served the double purpose of keeping the road wheels on the track and of transmitting the drive by engaging with a roller-type sprocket. The pitch of Christie's track was 248mm, which was even longer than the 190mm pitch of the original British tank tracks. It was, therefore, noisy but because it was relatively light it was much more suitable for use at high speeds. In fact, it was with such a track, with a pitch of 254mm, that Christie achieved in 1928 a speed of 68 km/hr, which was considerably higher than the maximum speed of any tank built until then. Christie's type of track was subsequently used on the Soviet BT and, in a strengthened form, on the T-34 tanks but with the pitch very sensibly reduced to 170mm.

The second major advance on the original type of track took place in the mid-1920s with the introduction on the Carden Loyd tankettes of a light-weight, short-pitch track with simple links of malleable cast iron. The links had a single spud and two guide horns and in the case of the Carden Loyd Mark VI, which was the first to be produced with this type of track in quantity, they were 133mm wide while their pitch was only 44.5mm. As a result this type of track was much quieter than others and it proved successful on light tanks, helping them to attain road speeds of 40 km/hr, or more. It also proved relatively durable and its introduction did much to advance the development of faster tanks.

Tracks of malleable cast iron were also used at the beginning of the Second World War on a number of heavier vehicles, such as the British A.9 cruiser tank and the Valentine infantry tank. However, by then another and much better type of track had been introduced. In principle its design followed the example set by the tracks of the Carden Loyd Mark VI but its skeleton-type links were of work-hardening manganese steel, which made them stronger and more durable. This type of track appears to have been introduced in 1928 on the Vickers-Armstrongs Six-Ton Tank and was subsequently adopted on its Soviet copy, the T-26, as well as German and other tanks.

Tracks with cast manganese steel links of skeleton type having a single central guide horn and at least three lugs on one side and four on the other became widely used during the Second World War on British and German tanks and they then continued to be used on British tanks such as the Centurion and on Soviet tanks such as the T-54. They still represent the lightest type of tank track but their steel spuds or grousers can cause severe damage to roads and their plain pin joints are open to the entry of abrasive dirt, which can cause rapid wear of the pins and of the holes in the lugs of the links.

Several attempts have been made to improve on the dry pin type of track by the use of such things as mud seals for the pin joints, which were fitted in the British Tetrarch light tank of the late 1930s. Another attempt involved the development of lubricated joints, which were incorporated as early as 1921 in the design of the British Light Infantry Tank and of the US Medium M1921 tank. However, none of these attempts proved successful, except for the tracks with sealed, lubricated pin joints with needle bearings which were developed in Germany during the 1930s and which were used during the Second World War on three-quarter track armoured personnel carriers as well as other vehicles. But tracks of this type were relatively heavy as well as expensive to produce and they were not adopted for tanks.

Fig. 13.14 All-steel, single-pin tracks fitted to a prototype of the British Chieftain tank.

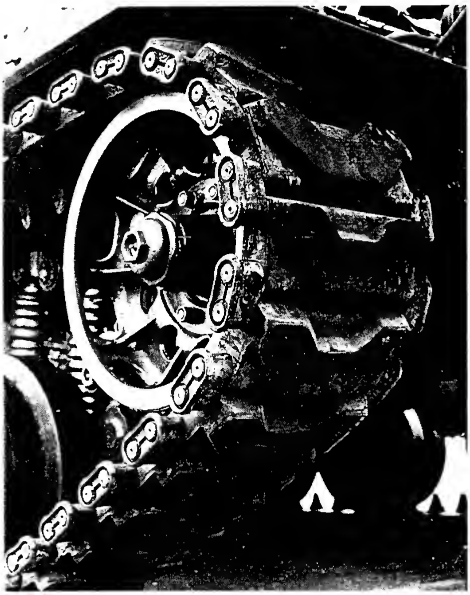


Fig. 13.15 An early type of a single block, rubber-bushed, double-pin track.

Instead tanks have come to use to an increasing extent another alternative to the dry pin type of track in the form of the rubber bushed track. In this type rubber bushes eliminate metal-to-metal contact between the pins and the links and the necessary angular movement between them is provided by torsion of the rubber, the outer surface of the bushes being fixed to the links and the inner surface to the pins.

In its original form, introduced in 1934 on the US T2 light tank, the rubber bushed track consisted of blocks each of which contained two pins in rubber bushes. The pins were fixed at each end to steel connectors which provided a rigid bridge between the pins of adjoining blocks. In the case of wide tracks two blocks were used side-by-side, with two long pins for each pair of blocks and a central connector-cum-track guide as well as the end connectors.

Double pin tracks became almost the only ones to be used on US tanks until the later stages of the Second World War but the double block version of them did not come into use until 1944, when a 584mm wide track of this type began to replace the earlier, 420mm wide, single block tracks on M4 medium tanks. Since then double-pin, double-block tracks have been used on all US medium and heavy tanks. During the 1960s they were also adopted on German tanks and then on an increasing number of others, including the Japanese Type 74, the Engesa Osorio and the Soviet T-64. In fact, they have become the norm for battle tanks.

On the other hand the single block version of the double pin track, which was originally used on US light tanks, has been superseded to some extent since the Second World War by tracks with single, rubber-bushed pins. The latter resemble the all-steel skeleton or recessed link type of track but instead of having plain pin joints the lugs of its links are rubber bushed, so that relative motion between the pins and the links is provided by torsion of the rubber, as in the double pin tracks, and not by metal-to-metal sliding. However, the length of the rubber bushes in single pin tracks is only half of what it is in corresponding double pin tracks. They can not, therefore, transmit equally large forces. In consequence, the use of single-pin, rubber bushed tracks has been confined to lighter vehicles, the heaviest tanks to have them being the 39-ton Swiss Pz.68 and the 41ton Soviet T-72.

Where they can be used, single pin tracks have the advantage over the double pin tracks of being potentially lighter, although in several cases there has been virtually no difference in their weight. For instance, the T130 single pin track of the widely used US M113 armoured carrier has a mass of 64kg per metre of its length while the 213 double pin track produced for it by the Diehl company has a mass of 63 kg/m. However, in the case of the British Scorpion light tank the standard single pin track has a mass of 39.7 kg/m, whereas the alternative Diehl 338 double pin track has a mass of 50 kg/m.

The adoption of rubber bushes for track pins has been accompanied by the use of rubber for the outer faces of track links and in many cases also for the inner faces on which the road wheels run. The links of the original US double pin tracks were actually encased in rubber and were reversible. But this meant that both their faces had to be flat, whereas the outer faces need to have grousers for better traction in muddy ground. Since the outer faces were subject to greater wear it was inevitable that they should be made in the form of replaceable pads, which were incorporated in the mid-1960s in the double pin tracks of the US-German MBT-70 and which were put into service in the mid-1970s on the German Leopard 1 and also the US M60A1 with the adoption of the T142 track.

The bonding of rubber on the inner faces of track links has been something of a mixed blessing for while it helps to attenuate track induced vibrations it also

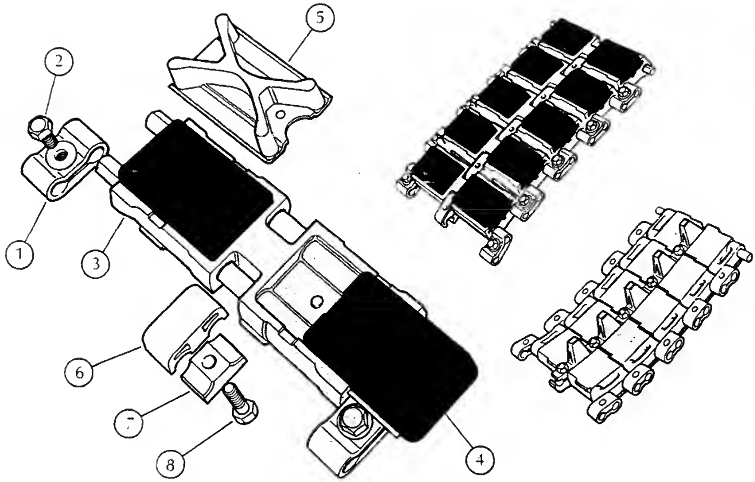


Fig. 13.16 Components of a track link and, right, complete sections of the Diehl double-pin track used on the German Leopard 2 tank:
1 = End connector
2 = End connector bolt
3 = Track link body with integral centre guide
4 = Replaceable rubber track pad
5 = Grouser which can replace a track pad
6 = Centre connector, outer part
7 = Centre connector, inner part
8 = Centre connector bolt

increases the weight of the links and, what is more, increases the rolling resistance. It has therefore been used on some tanks, such as the US M48 and the German Leopard 1, but not on others, such as Leopard 2.

The original single-pin, rubber-bushed track, which was incorporated in the design of the US T4 Combat Car built in 1933, and the first tracks of this type to be put into service in 1944, on the US M18 tank destroyer and the M24 light tank, did not have rubber road pads or rubber inner faces. But since the introduction of the US M41 light tank in 1951 it has been general practice to provide single-pin, rubber-bushed tracks with replaceable road pads and, as often as not, to bond rubber on to their inner faces. In some cases, the most notable of which has been the T138 track of the US M551 Sheridan light tank, the rubber road pads have been bonded on to the track links. This made the latter somewhat lighter and eliminated the risk of the pads breaking and flying off but, of course, it also sacrificed the ability of extending the life of the track by replacing the pads.

During the 1960s replaceable as well as bonded rubber road pads also began to be incorporated in the design of the dry-pin steel tracks. This has been done mainly to reduce the damage caused by such tracks to road surfaces but it has made the tracks less effective than they had been off the roads, particularly with regard to traction in cohesive clay soils.

As a result of all the development of them, the life of tank tracks has increased

very considerably over that of the original British Mark I tanks of 1916. The latter was estimated to be not more than 30km, although it actually exceeded 60km (13.32). Thus, by the time the short-pitch manganese steel tracks were introduced in the late 1920s, the tracks of light tanks such as the Vickers-Armstrongs Six-Ton Tank were claimed to have a life of 4800km, or more (13.33). In fact, a track life of 4000 to 8000km was achieved during the mid-1930s by tanks such as the 10.5-ton T-11 built in Czechoslovakia by Skoda (13.34). However, the life of the dry-pin tracks of the heavier tanks used during the Second World War was generally considered to be no more than 1000 to 1500km. The latter figure was also considered to apply to the tracks of post-war tanks, such as the British Centurion.

The double-pin, rubber-bushed tracks introduced before the Second World War on US light tanks had a life of the order of 6000km but similar tracks used during the war on US M3 and M4 medium tanks had an average life of 2400km (13.35). Double-pin tracks of the T80 series introduced during the latter part of the war and used later on the US M46 and M47 medium tanks were reputed to have a longer life of about 6000km (13.36). But another track of this type, the T97E2 used on the US M60 tanks, was reported in the mid-1960s to have a life of 3500km. The single-pin, rubber-bushed tracks of the Swiss Pz.68 were expected to have a life of 2500km but it proved to be NO more than 1000 to 2000km.

Further development in the United States resulted in the T142 double-pin track which, when it was introduced on the M60A1 tanks in the mid-1970s, was expected to have a life of as much as 8000km and its replaceable pads were expected to last 4000km. However, the more highly stressed tracks of the US M1 tank were only required to have a life of 3200km. During tests carried out around 1980 their actual life proved to be no more than 1690km, although the T156 tracks with which the M1 tanks were subsequently fitted have had a longer life of between 2000 and 2900km.

The less highly stressed tracks of lighter vehicles have become more durable. For example, the single-pin, rubber-bushed tracks of the US M41 light tank attained a life of more than 6400km during tests carried out around 1951 (13.37). The T130 single-pin tracks of the M113A1 armoured carrier proved to have a somewhat shorter life of about 5400km when tested in Vietnam during the 1970s. But the single-pin tracks of the US LVTPX12 amphibious carriers which were tested at about the same time attained an average life of 13 750km and the M70 tracks of the contemporary Swedish Pbv 302 armoured carrier have had a life of 10 000km.

Thus, although some of the expectations have not been met and in spite of considerable variations between tracks of the same type, their average life has increased considerably over the years. But improvements in track life and in such things as damage to road surfaces have been accompanied by undesirable changes in other respects, such as increased weight, greater cost and longer pitch.

The increases in weight are illustrated by a comparison between the rubber-padded, double-pin track of the US M47 tank and the all-steel, dry-pin track of the British Centurion. The two tracks are of approximately the same width but the former has a mass of 155 kg/m compared with 132.5 kg/m of the latter. Given that a typical battle tank track has a length of about 15m, this implies a difference of 675kg per vehicle.

The lengthening of the track pitch is exemplified by the double-pin tracks of the US M48 and M60 tanks, which have a pitch of 176mm, and even more by the track of the German Leopard 2, which has a pitch of 183.5mm. This is not only

more than the pitch of dry-pin tracks, such as that of the Centurion which is 140mm, but is even more than the 170mm pitch of the Christie type track of the Soviet T-34 tank, which has been criticised for it in the past. A point in favour of long pitch is that it reduces the extent to which the ground pressure rises under the road wheels above its average value and it is particularly strong in relation to the tracks of battle tanks whose average ground pressure is inevitably high. But long pitch aggravates the problem of track noise and of track induced vibrations. This weakens the case for it, especially when it comes to vehicles lighter than battle tanks, which can have a relatively low average ground pressure. In particular, it is difficult to justify a pitch of as much as 152mm for the tracks of a relatively light vehicle like the M113 armoured carrier and all the more so when other vehicles of approximately the same size, such as the British FV 432 and the Swedish Pbv 302, have tracks with a pitch of 117 and 110mm, respectively.

The advantages of short pitch are demonstrated by the long life of the tracks of the Pbv 302, which has been mentioned earlier, and by them being considerably quieter. In fact, the noise level of the Pbv 302 was reduced by 10 dB by fitting it with the short pitch tracks instead of its original long-pitch tracks of the same kind as those used on the M113. In the M113A1 itself the track induced noise level exceeds 100 dB, which is deafening and calls for the use of hearing protectors by the crew.

The other major dimension of the track links, namely their width, has been closely related to ground pressure, which in this context is the load per unit of the projected area of the tracks in contact with the ground. This does not represent the actual pressure exerted by tanks on the ground but is, nevertheless, an indicator of their ability to move over soft ground, which increases as its value decreases. In consequence, low ground pressure has been a major objective of tank design and to achieve it attempts are generally made to provide tanks with tracks which are as wide as possible or practicable.

The outcome of it has been that recently designed light tanks and other light armoured vehicles have tracks with a width ranging from about 300 to 450mm, which has met the objective of a low ground pressure to a degree that varies considerably. Thus, the ground pressure of tracked armoured vehicles other than battle tanks ranges from as little as 36.2 kN/m^2 of one of the lightest of them, the British Scorpion light tank, to almost 80 kN/m^2 of some of the heaviest.

The ground pressure of battle tanks is generally higher than that of light armoured vehicles even though their tracks are wider. This is inevitable because the width of the tracks can not be increased in proportion to the weight of tanks without encroaching unduly on the width of the hulls or exceeding the limits imposed on the overall width of tanks by the existing transportation facilities. Thus, battle tanks have tracks with a width ranging from 500 to 710mm and their ground pressure varies from just under 80 kN/m^2 of the lightest of them to as much as 98 kN/m^2 of the heaviest, such as the British Challenger tank.

In addition to meeting the requirements of movement over soft ground, which are represented by the nominal ground pressure, or NGP, the design of tracks also has to take into account the pressure acting on the track pads when tanks are moving on roads. This pressure is much higher than NGP because on hard surfaces the whole of the load carried by a road wheel can act on a single track link and the surface area of the road pads is only equal to 30 or 40 per cent of the nominal area of the track links represented by the product of their width and their pitch. Thus, as the road wheels roll over the track on hard ground and the whole of the load acting on a road wheel is transferred on to a single link, the pressure over

the face of the track pad rises to between 9 and 15 times the NGP. This means that the average maximum pressure over the face of the pads can range from 400 kN/m^2 in the case of light armoured vehicles to 1200 kN/m^2 in the case of battle tanks. High values of this pressure inevitably lead to rapid wear of the pads.

13.10 References

13.1 M G Bekker, *Introduction to Terrain-Vehicle System*, University of Michigan Press, Ann Arbor, 1969, pp.512-524.
13.2 *Ride and Vibration Data Manual*, Society of Automotive Engineers, New York, 1965.
13.3 B G Schreiner and W E Willoughby, *Validation of the AMC-71 Mobility Model*, Proc. 5th Int. Conf. of Int. Soc. for Terrain-Vehicle Systems, Detroit, 1975.
13.4 D Cardwell, 'The Acceleration of Military Vehicles During Cross-Country Operation,' *Advances in Automobile Engineering*, ed. G H Tidbury, Pergamon, Oxford, 1963.
13.5 B D Van Deusen, *Human Response to Vehicle Vibration*, SAE Paper No.680090, Society of Automotive Engineers, New York, 1968.
13.6 *Guide for the Evaluation of Human Exposure to Whole-Body Vibration*, ISO 2631, International Standards Organization, 1978.
13.7 R A Lee and F Pradko, *Analytical Analysis of Human Vibration*, SAE Paper 680091, Society of Automotive Engineers, New York, 1968.
13.8 M P Jurkat, C J Nuttall and P W Haley, *The US Army Mobility Model (AMM-75)*, Proc. 5th Int. Conf. of Int. Soc. for Terrain-Vehicle Systems, Detroit, 1975, p.1-11.
13.9 N R Murphy and R B Ahlvin, *AMM-75 Ground Mobility Model*, 5th Int. Conf. of Int. Soc. for Terrain-Vehicle Systems, Detroit, 1975, p.3-23.
13.10 M P Jurkat et al., op.cit., p.1-12.
13.11 R A Anderson, *Fundamentals of Vibrations*, Macmillan, New York, 1967.
13.12 E Lehr, *The Springing and Damping of the Suspension of Armoured Vehicles*, (translation), Ministry of Armaments, Berlin, 1944.
13.13 E B Maclaurin and J W Elder, *Design of Off-Road Vehicles for Higher Speeds*, Conf. on Off-Highway Vehicles, Tractors and Equipment, Inst. Mech. Eng., London, 1975.
13.14 M G Bekker, *Theory of Land Locomotion*, University of Michigan Press, Ann Arbor, 1956, pp.370-379.
13.15 M G Bekker, *Introduction to Terrain-Vehicle Systems*, op.cit., pp.181-191 and 504-512.
13.16 H E Merritt, *Some Considerations Influencing the Design of High-Speed Track Vehicles*, Proc. Inst. Automobile Engineers, Vol.33, 1938-39, p.418.
13.17 US Patent 1,836,446, 1931.
13.18 T Franzen, *Suspension and Track of German Military Track Laying Vehicles*, SAE German Engineering Evaluation Meeting, Society of Automotive Engineers, New York, 1946.
13.19 R W Siorek, *Experimental Investigation of Effect of Wheel Travel on Tracked Vehicle Mobility*, SAE Paper 730036, Society of Automotive Engineers, New York, 1973, p.2.
13.20 E Lehr, op.cit.
13.21 E N Cole and H G Warner, *Walker Bulldog – Its Design and Production*, Society of Automotive Engineers, Detroit Section, 1951.
13.22 B W Long and A Comito, *Development of Armored Personnel Carrier M113A1E1*, SAE Paper 790414, Society of Automotive Engineers, Warrendale, 1979.
13.23 B Maclaurin, *Progress in British Tracked Vehicle Suspension Systems*, SAE Paper 830442, Society of Automotive Engineers, Warrendale, 1983.

13.24 S L Varner. 'Automatic Ride Control', *Ordnance*, Vol.48, No.262, January-February 1964, pp.454-456.
13.25 G V Cleare. *Factors Affecting the Performance of High-Speed Track Layers*, Proc. Inst. Mech. Eng., Vol.178, Part 2A, No.2, 1963-64, p.53.
13.26 R E Jones, G H Rarey and R J Icks, *The Fighting Tanks since 1916*, National Service Publishing Co., Washington, 1933, p.166.
13.27 P Touzin, *Les Vehicules Blindés Français 1945-1977*, Editions EPA, 1978, p.60.
13.28 *Automotive Suspensions*, AMCP 706-356, US Army Materiel Command, Washington, 1967, p.10-15.
13.29 *The Automotive Assembly*, AMCP 706-355, US Army Materiel Command, Washington, 1962, p.11-22.
13.30 Ibid., p.11-22.
13.31 R M Ogorkiewicz, 'Plastics in the Design of Military Equipment', *The Engineer*, Vol.215, No.5596, 26 April 1963, pp.755-756.
13.32 *Short History of the Royal Tank Corps*, Gale & Polden, Aldershot, 1945, p.20.
13.33 R E Jones et al., op.cit., p.130.
13.34 L B Magruder, *History of Development of Tank Design at the Skoda Works in Pilsen*, CIOS Target No.18/93, Combined Intelligence Objectives Sub-Committee, SHAEF, 1945, p.4.
13.35 *Automotive Suspensions*, op.cit., p.10-77.
13.36 Ibid., p.10-77.
13.37 E N Cole et al., op.cit., p.9.

Chapter 14

Soil-Vehicle Mechanics

14.1 Characteristics of Soils

Since tanks are meant to operate over soft, deformable soils as well as other types of terrain, their design differs from that of vehicles intended only for operation on roads. In particular, it has to take into account the deformation of the soils which tanks cause and the effect this has on their performance. This has been attempted in many different ways, some of which may appear to have little in common but which generally have the same broad objectives. These amount to the development of methods of predicting whether or how well tanks will operate over soft soils, and through the resulting knowledge of the relationships between vehicle performance and soil characteristics, to helping improve the design of tanks.

Some of the methods which have been developed do no more than indicate the soft soil performance of tanks in very broad terms. Such methods have their uses but it is obviously desirable to be able to predict the performance of tanks with precision, which has led to the development of increasingly elaborate and sophisticated models of the relationship between it and the characteristics of soils. However, the relationship is difficult to model accurately because of the complexity of the interactions between vehicles and soils. Moreover, the development of models is greatly complicated by the variety of types of soils and the spacial and temporal variation of their properties.

Types of soils range from gravel and sand to silt and clay and include organic soils, such as peat and muskeg, as well as snow-covered ground. Soils are made up of particles of various sizes and they are generally classified according to the predominant particle size. Thus, they are divided into coarse-grained soils, which include gravel and sand, fine-grained soils, which include silt and clay, and organic soils, which contain a large percentage of organic matter (14.1).

Of the two types of soils which are of particular interest, dry sand has no cohesion and its resistance to shear, by which soils usually fail when stressed by tank tracks, depends on internal friction and, therefore, on the normal pressure exerted on it. The other type of soil of interest is saturated clay which is cohesive and its shear strength is independent of the normal pressure. However, most soils on which tanks operate and in particular the normal agricultural soils, or loams, are mixtures of sand and clay as well as organic matter. In consequence, they exhibit both cohesive and frictional characteristics.

In addition to being dependent on their composition, the strength of soils also depends on their moisture content and therefore on the rainfall. This is particularly true of clay soils, which can turn from being relatively hard when sun-baked

into sticky mud after a rainstorm. Coarse-grained soils are less affected by water because the voids between their particles are larger and they drain more rapidly. However, the amount of water retained by soils depends also on topography, low-lying areas such as river valleys where the water table is not far below the surface having a higher moisture content than areas of higher ground.

In contrast to the reduction in the strength of soils with moisture content at normal temperatures, when temperatures fall and the water present in them freezes then both sandy and clay soils become hard to almost the same degree.

14.2 Nominal Ground Pressure

The earliest and still the most widely used basis of relating tanks to soft soils is a measure which has become known as nominal ground pressure, or NGP. This is the weight of a vehicle per track divided by the product of the overall width of the track and of its length in contact with the ground.

The use of NGP arose, no doubt, out of the obvious fact that the sinkage of vehicles into soft soils hinders their movement and that it depends on how heavy they are in relation to the area of the ground on which their weight acts or, in other words, on their ground pressure. NGP does not represent the actual pressure exerted by tanks on the ground but it was a reasonable approximation to it in the case of the early tanks, which ran on small unsprung rollers and had tracks with rectangular, flat-plate links. Its very approximate nature may not have been recognised at first but it was accepted as an important characteristic of tanks, being quoted as such as early as 1917 (14.2). Moreover, the achievement of low NGP became a feature of some of the earliest tank designs (14.3).

Initially there was little if any experience to indicate what the NGP should be and in the circumstances comparisons were made with the pressure exerted on the ground by a man's foot when the whole of his weight was acting on it, the implications of this being that tanks should be able to move over the same ground as infantrymen (14.4). This led during the 1920s to the view that NGP should not be much more than about 50 kN/m^2 (14.5). In fact, the most numerous light tank of the period, the Renault FT, had an NGP of 58 kN/m^2 and in most light tanks built during the 1930s it ranged from 40 to 70 kN/m^2.

Values as low as this were difficult to achieve with heavier tanks and during the late 1930s the NGP of medium, heavy and even of some light tanks rose to more than 80 kN/m^2 and in a number of cases it exceeded 100 kN/m^2. Some increase in NGP was unavoidable as tanks grew heavier but it need not have risen anywhere near 100 kN/m^2 because contemporary tanks could have been fitted with wider tracks. This was shown very clearly in 1941 by the Soviet T-34 which had an NGP of 63 kN/m^2 and even more by the 42.5 ton KV heavy tank which still had an NGP of only 78.5 kN/m^2. However, it was only during the Second World War that the importance of NGP was generally recognised. Thus, in spite of it being noted during the First World War, little if any attention appears to have been given to NGP in the military requirements of the 1920s and 1930s.

The subsequent recognition of the importance of keeping NGP low resulted towards the end of the Second World War in tanks being fitted with wider tracks and consequently having an NGP no higher than that of the earlier tanks in spite of a general increase in weight. Thus, the 44.8 ton Panther had an NGP of 84.9 kN/m^2 and the 69.7 ton Tiger II, the heaviest tank used during the war, had an NGP of 105 kN/m^2. The improvement was maintained during the 1950s when, for instance, the 50.8 ton Centurion 5 had an NGP of 89.8 kN/m^2, compared with

101 kN/m^2 of the much lighter, 19.3 ton Crusader II of 1942. What is more, the heaviest tank of the period, the 66 ton Conqueror, had an NGP of only 83.1 kN/m^2, thanks to its exceptionally wide tracks and long length of contact with the ground.

Constraints imposed by transportation requirements on the overall width of tanks and hence on the width of their tracks have caused the NGP of some of the most recent tanks to rise again to almost 100 kN/m^2. In particular, the 62 ton Challenger and the 60 ton Merkava Mark 2 have an NGP of 97.6 and 96.2 kN/m^2, respectively. On the other hand, the NGP of some of the light tanks, such as the 7.9 ton Scorpion, has been only 36.2 kN/m^2.

The relationship between NGP and the weight of tanks is illustrated in Fig. 14.1, which shows a plot of one against the other for tanks and other tracked armoured vehicles built since the closing stages of the Second World War. There is obviously considerable scatter in the plot but the straight line, which corresponds to the lowest of NGP that have been achieved, shows clearly that it increases with vehicle weight.

NGP can also be plotted against weight for wheeled armoured vehicles, its value in this case being equal to the weight per wheel divided by the product of the width of its tyre and of an approximation to the length of the area of contact between the tyre and the ground. The results are shown in Fig. 14.2, where there is again considerable scatter and where the straight line represents the lowest values that can be achieved. Comparison of this line with that in the previous figure throws light on the perennial question about the use of wheels instead of tracks. In particular, when the two lines are compared, as they are in Fig. 14.3, it is clear that the NGP of wheeled vehicles is not only higher than that of tracked vehicles but that it rises more rapidly with vehicle weight. In consequence wheeled vehicles

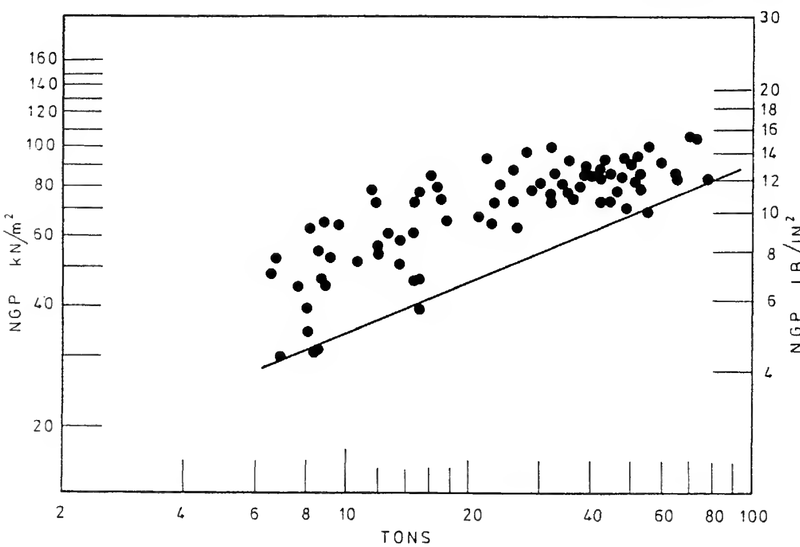


Fig. 14.1 Nominal ground pressure of tanks and other tracked armoured vehicles plotted against their weight.

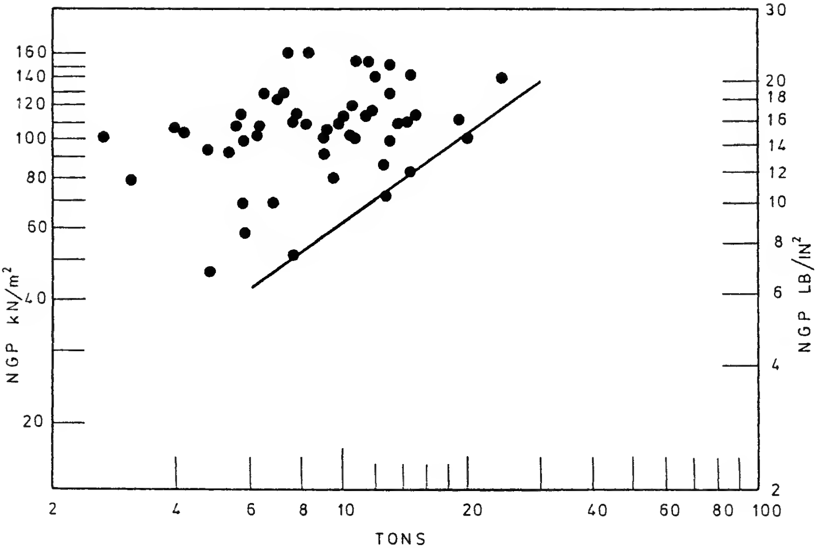


Fig. 14.2 Nominal ground pressure of wheeled armoured vehicles plotted against their weight.

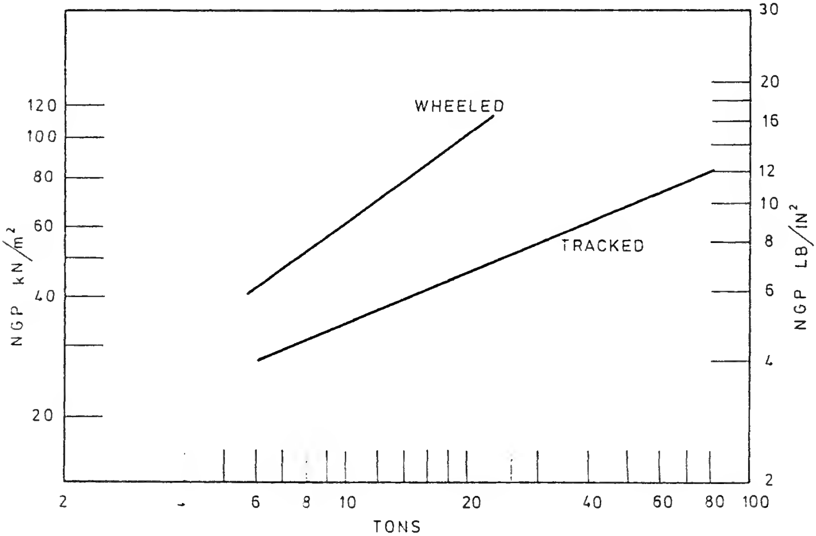


Fig. 14.3 Comparison of the minimum ground pressures of tracked and wheeled armoured vehicles.

reach the limits of NGP from the point of view of soft soil operation at much lower weights than tracked vehicles. This indicates that wheeled armoured vehicles may be competitive when they are very light but that they become progressively less attractive as their weight increases and they cease to be a practical proposition at a weight level considerably lower than that of tanks.

In addition to providing a numerical basis for comparing the soft ground capabilities of vehicles and a guide to the design of tracks, NGP has also been used to assess the ability of vehicles to operate over different soils by associating the latter with particular values of it. Thus, NGP of not more than 80 kN/m^2 came to be considered necessary for good performance over muddy ground and of about 40 kN/m^2 for operation over peat. Similarly, NGP of less than 15 kN/m^2, which is much lower than that achieved with any tank, has been considered necessary for crossing swamps or for moving over ground covered by some kinds of snow.

The association of the limiting values of NGP with particular soils, or soil conditions, amounted to an attempt to characterise the latter in quantitative terms from the point of view of the movement of vehicles over them. As such it could be regarded as an advance on the purely qualitative description of soils. But the quantitative alternative which it offered was very broad and not based on physical measurement but only on judgement.

14.3 Mean Maximum Pressure

On the whole, NGP has proved useful as a measure of the ability of tanks to move over soft soils and in particular for assessing their relative capabilities. Thus, tanks with a low NGP have generally performed better over soft soils than similar tanks with a high NGP. However, NGP is no more than a gross approximation to the pressure exerted by tanks on the ground and fails to take into account the fact that the pressure varies along the length of the track. In particular, it fails to take into account that peaks of the pressure, which occur under the road wheels, can be considerably higher than its average value.

The variation in pressure was relatively small in the case of the original tanks as their tracks were almost rigid but as tracks became more flexible and the small unsprung rollers were replaced by large, sprung road wheels the variation became considerable. NGP provided no indication of this and yet it is the peak values of the pressure rather than its average which governs sinkage and therefore the performance of tanks on soft soils. As a result, NGP failed to provide a correct measure of the relative performance capabilities of vehicles which had similar values of it but differed in the number of road wheels and in track pitch and which, because of this, had different peak pressures.

The fact that ground pressure varies along the track was recognised in Britain even before the Second World War, when it was suggested that its maxima under the road wheels might be equal to two to four times its average value and that NGP can be misleading (14.6). The truth of this was demonstrated a little later by experiments carried out in the Soviet Union in which the NGP was kept constant and the skinkage was shown to vary with the number of the road wheels, decreasing as their number increased (14.7).

Other experiments, carried out in Britain towards the end of the Second World War and afterwards, demonstrated further the shortcoming of NGP and the importance of the peak pressures. One of the most telling of them involved a Churchill tank which had the number of its road wheels reduced from eleven to seven per side. This increased the average of the peak pressures under its tracks by

80 per cent and more than doubled their sinkage, in spite of the fact that the NGP remained unchanged. In another experiment with a Cromwell tank the pitch of the track links was doubled and this reduced the average of the peak pressures by 29 per cent and the sinkage by 33 per cent although, once again, the NGP remained unchanged.

Physical reasoning leads to the conclusion that the maximum pressure under a track P_{max} must be directly related to the weight acting on each of the road wheels and inversely related to the width of the track, the pitch of its links and the diameter of the road wheels, or that,

$$P_{max} \propto \frac{W}{2\ n\ b\ \ f(p,d)} \quad \ldots\ldots 14.1$$

where W = weight of vehicle, kN
n = number of road wheels per side
b = width of track, m
p = pitch of track links, m
d = diameter of road wheels, m

Such an expression was derived by D Rowland who correlated it with pressures recorded during the experiments carried out in Britain with some 21 different tanks and other tracked vehicles, mostly in cohesive soils. This produced the following equation for the mean maximum pressure, or MMP, the mean value of the maxima of the pressure under the tracks:

$$MMP = \frac{0.63\ W}{n\ b\ c\ \ (pd)^{0.5}} \quad \ldots\ldots 14.2$$

where c is the ratio of the actual plan area of a track link to the product of p and b (14.8).

Rowland proposed that MMP should replace NGP as a design parameter and be used as the basis of comparing the soft soil performance capabilities of vehicles. This has happened to some extent since the use of MMP was first proposed in 1972 and comparisons of the values of it calculated using equation 14.2 with known records of the performance of a number of tanks have shown that it is a far more accurate measure of their capabilities than NGP. For instance, the NGP of 84.9 kN/m^2 of the German Panther of the Second World War and the 94.6 kN/m^2 of the contemporary US M4 medium tanks did not reflect how superior the performance of the former was generally considered to be in relation to that of the latter. But their respective MMPs of 157 and 272 kN/m^2 reflect this very clearly.

An even better example of the superiority of MMP over NGP as a measure of the capabilities of tanks is provided by the British Matilda infantry tank which had a higher NGP than any other tank used during the Second World War and which might have been expected therefore to perform badly on soft soils. In fact it was never seriously criticised on account of its soft soil performance, in spite of being used not only in Europe and East and North Africa but also, by the Australian Army, in New Guinea and other Pacific islands. The underlying reason for this apparent paradox was that, although the NGP of the Matilda was as high as 112.4 kN/m^2, its MMP was only 252 kN/m^2, according to equation 14.2, which

Table 14.1 **NGP and MMP* of Typical Vehicles**

Vehicle	Mass kg	NGP kN/m^2	MMP kN/m^2
Matilda	26 920	112.4	252
Covenanter	18 300	102	390
Cromwell IV	27 940	103.2	368
Panther	44 800	84.9	157
Tiger II	69 700	105.2	190
Centurion 5	50 800	89.8	275
Conqueror	66 000	83.1	247
Chieftain 5	55 000	92.5	279
Challenger	62 000	97.6	285
T-54	36 000	79.3	242
T-72	41 000	78.2	239
AMX-30	36 000	80.7	245
Leopard 1	42 400	89.6	223
Leopard 2	55 150	86.1	223
M60A1	47 600	77.6	206
M1	54 500	90.5	231
M551	15 250	47.2	162
M113A1	11 160	53.8	121
Scorpion	7 940	36.2	101

*Calculated from Equation 14.2

was no higher than that of many other tanks. On the other hand, the contemporary British Covenanter tank was criticised for its performance over soft soils although its NGP of 102 kN/m^2 was lower than that of the Matilda. But the criticism can be easily accounted for by its MMP, which was no less than 390 kN/m^2 and as high therefore as that of some wheeled armoured vehicles.

To minimise their MMP, tanks should obviously have the maximum possible number of road wheels and, therefore, wheels of small rather than large diameter. They should also have long pitch tracks. But this clashes with other requirements, which makes compromises inevitable. The actual values of MMP of recently produced battle tanks range from 206 kN/m^2 of the US M60A1 to 285 kN/m^2 of the heaviest, the British Challenger, while those of light tanks and armoured carriers are generally below 200 kN/m^2 and as low as 101 kN/m^2 in the case of the Scorpion light tank.

MMP varies with the weight of tanks like their NGP. The MMP of wheeled armoured vehicles also varies with their weight like their NGP and the pattern of the difference between the MMP of tracked and wheeled vehicles is much the same as that of the NGP illustrated in Fig. 14.4. However, MMP allows the two types of vehicles to be compared more accurately than NGP.

On cohesive, clay soils, to which equation 14.2 applies, the MMP of recently built tanks is equal to between 2.3 and 3.0 times their NGP. This relatively fixed relationship between it and NGP indicates that there is generally little difference between the running gear of tanks and that NGP can be used to compare their soft soil capabilities with almost the same accuracy as MMP. However, MMP remains fundamentally the more accurate basis of comparisons and can bring out the influence of design details which NGP can not do.

On other soils the ratios of MMP to NGP are different from those on cohesive, clay soils because MMP varies with the strength of the soil and its values differ in consequence from those given by equation 14.2. In fact, on very firm soils MMP

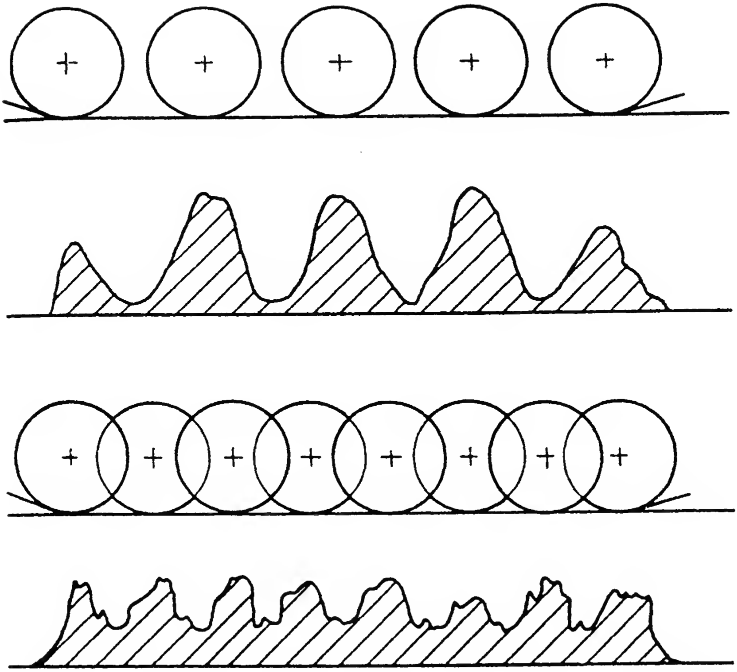


Fig. 14.4 Variation of pressure under the tracks of two tanks with similar nominal ground pressures but different numbers of road wheels and, consequently, different mean maximum pressures: top, Comet with NGP = 98.5 and MMP = 306 kN/m² and, bottom, Panther with NGP = 87.5 and MMP = 150 kN/m².

tends towards the pressure over the face of track pads when the load on a road wheel is transferred on to a single track link, while on exceptionally soft soils it tends in value towards the NGP. But the variation of MMP with the type of soil does not alter its usefulness as a measure of the relative soft soil capabilities of tanks.

As in the case of NGP, MMP can be used not only for comparing the capabilities of vehicles over a particular type of soil but also for assessing their ability to operate over different types of soils by associating the latter with particular values of it. Thus, an MMP of 200 kN/m² based on equation 14.2 has been suggested by Rowland as the maximum that vehicles should have for satisfactory operation on wet, fine-grained, i.e. clay, soils in temperate zones and 140 kN/m² for operation on similar soils in tropical zones (14.9).

Rowland also correlated MMP with the strength of soils, characterised by means of cone penetrometers, that will only just allow vehicles to pass over them and this is dealt with in the following section.

14.4 Characterisations based on Cone Penetrometers

Any attempt to advance from a general numerical characterisation of the capabilities of tanks to quantitative relationships between their performance and soils requires the adoption of some measure of soil properties. The most widely used of such measures is the resistance of soils to the penetration by a single instrument called the cone penetrometer. The resistance is recorded in terms of the cone index, which is the force required to push the penetrometer into the soil per unit of the base area of its conical head.

The use of cone penetrometers arose out of the need for a method which could be used in the field to assess whether or not vehicles could travel over particular areas of the ground encountered in the course of military operations or, in other words, to measure the trafficability of soils. The probing of the ground which it involves was practiced already during the First World War by British tank officers who used walking sticks as probes to decide whether their tanks could move over particular areas of ground (14.10). The use of walking sticks developed to the point where the force required to push them into soils was related to the pressure the soils could bear and therefore verged on becoming a quantitative assessment of soils (14.11). Thus, the use of walking sticks to probe the ground foreshadowed the employment of penetrometers and has been commemorated by the 'ash plants' which have become part of the uniform of the officers of the Royal Tank Regiment.

Cone penetrometers were developed for military purposes by the Waterways Experiment Station of the US Army Corps of Engineers, which began to investigate the trafficability of soils towards the end of the Second World War (14.12). Prior to this soil penetrometers had already found use in civil engineering and in at least one study of the performance of agricultural tractors (14.13). In the form adopted by the Waterways Experiment Station, or WES, the penetrometer consists of a rod having a right circular, 30° cone with a base area of 323mm^2 at its lower end and a suitably calibrated gauge, as well as a handle, at the top end to measure the force applied to the handle to push the cone into the ground. The penetrometer is used by pushing it slowly at the rate of about 13mm/s and taking readings of the gauge at selected intervals to a depth, typically, of 150 or 300mm. The average of the forces applied over a given soil layer divided by the base area of the cone then gives the cone index, which in most cases has been quoted in lb/in^2, although the units have been generally omitted.

Values of the cone index in SI units range from 1500 kN/m^2 for dry grassland, or even 2000 kN/m^2 for coarse-grained sand and gravel, through 1200 kN/m^2 for sandy loams when their moisture content is low and 500 kN/m^2 when they are wet to 300 kN/m^2, or less, for peat and 200 kN/m^2 for wet, loose agricultural soil after ploughing.

Cone indeces obtained directly from measurements of the resistance to penetration have not proved an entirely adequate characterisation of soils from the point of view of vehicle movement, because the strength of fine-grained, cohesive, clay soils changes with the remoulding caused by the passage of vehicles over them. In consequence a supplementary test has been devised to assess the effects of remoulding. It involves confining a sample of the soil in a small cylinder and taking cone penetrometer readings in it before and after it has been pounded by 100 blows of a 1.1 kg hammer falling 0.3m. The ratio of the cone indeces after and before the pounding, called the Remoulding Index (RI), is taken to represent the action of a vehicle on the soil and is used as a correction factor of the cone index

(CI) values obtained in situ to obtain a Rating Cone Index (RCI). Thus,

$$\text{CI} \times \text{RI} = \text{RCI} \qquad 14.3$$

Values of RI range from 1.0 for coarse-grained, sandy soils to 0.2 for peat. A value of 0.8 is frequently taken for cohesive, clay soils without making actual measurements, because of the time they take.

Although RCI has come to be used as a more accurate measure of the strength of fine-grained, cohesive soils than CI, its use has destroyed some of the simplicity of the characterisation of soils by means of cone penetrometers, which is its greatest attraction. The same applies to another elaboration of cone measurements introduced to deal with frictional, sandy soils whose resistance to penetration increases with their depth. Thus, sandy soils have come to be characterised not by their CI but by the rate of increase of the CI with depth, which obviously requires additional measurements.

The adoption of cone penetrometers as the basis of characterising soils led WES to correlate cone indeces of fine-grained soils with the ability of vehicles to move over them. This has been done in terms of the Vehicle Cone Index, or VCI, which is the RCI of the weakest soil that will permit one or 50 vehicles of a particular type to pass over it. Thus, by comparing it with their RCI, the VCI of a vehicle identifies what soils it can or can not operate on. For example, the M60A1 tank has a VCI_1 of 138 kN/m^2 and can be expected therefore to pass once over soils with an RCI of that or of a higher but not of a lower value. Similar comments apply to its VCI_{50}, except that it corresponds to 50 vehicle passes and has an inevitably higher value of 331 kN/m^2. The VCI of lighter vehicles is, of course lower. For instance, the VCI_1 of the M551 Sheridan light tank is 97 kN/m^2 and its VCI_{50} is 221 kN/m^2.

The VCI of any particular vehicle can be determined by experiment but it is obviously much more economical to calculate it, if possible, from its design parameters and the ability to do this is essential for predicting the performance of new vehicles. Consequently a method of calculating VCI has been devised by WES, based on correlating it with the so-called Mobility Index of vehicles (14.14). Unfortunately, the Mobility Index is an incoherent collection of vehicle parameters and arbitrary factors and its adoption has marred the work done at WES on correlating the performance of vehicles with their design parameters and with the physical measurements of soils.

Another and more recent approach devised at WES to the empirical correlation of performance and vehicle parameters with cone index measurements has been more soundly based on dimensional analysis and has led to the use of what are called mobility numerics. These are non-dimensional groupings of vehicle and soil parameters which have been used to correlate experimental results and to derive empirical equations for the resistance to motion due to the deformation of soils and for the drawbar pull, that is the net thrust available for accelerating a vehicle or for moving it up slopes.

Mobility numerics were originally devised by D R Freitag to deal with pneumatic tyres on sand and clay (14.15). However, their use was then extended to tracks on sand by G Turnage, who derived for them the following numeric (14.16):

$$N_{ST} = \frac{G}{W}\,(b\;\;l\,)^{1.5} \qquad 14.4$$

where G is the rate of change of the cone index of a given soil with the depth of penetration, l is the length of track in contact with the ground and the other symbols are as defined in connection with equation 14.1. Using that numeric Turnage also derived the following equation for the drawbar pull F at a slip of 20 per cent, that is when the difference between the speeds of the tracks and of the vehicle is that percentage of the track speed, at which drawbar pull generally has its highest practicable value:

$$F_{20} = W\ (0.205 + 0.162 \log_{10} N_{ST}) \qquad \text{14.5}$$

No corresponding numeric appears to have been derived at WES for tracks on fine-grained, clay soils, although an empirical equation was produced there for the maximum drawbar pull achievable by tracked vehicle on such soils on the basis of the difference between their VCI and the RCI of the soils (14.17).

Although basically sound, the use of numerics like N_{ST} is of limited value because they do not characterise vehicles in greater detail than NGP and can not, therefore, bring out the effects of major differences in their design. A possible partial remedy for this are numerics incorporating MMP. A numeric of this kind has been proposed for tracks on clay but its usefulness is uncertain (14.18).

In the meantime a direct link has been established between MMP and cone penetrometer measurements in the form of simple equations connecting the MMP of a vehicle with the RCI of the weakest soil which will allow one or 50 passes by it, that is with its VCI_1 and VCI_{50} (14.19). The equations, which follow, apply to wet clay soils and the RCI as well as the MMP are in kN/m^2:

$$\text{1 pass RCI} = 1.86 \times \text{MMP} \qquad \text{14.6}$$

$$\text{50 pass RCI} = 0.66 \times \text{MMP} \qquad \text{14.7}$$

Empirical relationships have also been established between MMP, CI and the sinkage of the tracks, which are useful for predicting when a vehicle might belly, or what ground clearance it should have to avoid bellying. For clay soils, which generally pose more serious problems than sandy soils, the equation for sinkage z in terms of previously defined symbols is as follows (14.20):

$$z = 0.26\ n\ (p\ d)^{0.5} \left(\frac{\text{MMP}}{\text{CI}}\right)^{2.5} \qquad \text{14.8}$$

14.5 Semi-Empirical Models

Empirical relationships between vehicle and performance parameters and cone indeces can be very useful but they give little insight into the nature of the physical phenomena involved in the operation of vehicles on soft soils and their validity is generally limited to the range of conditions on which they are based. There is a need, therefore, for a more fundamental approach to the interaction between vehicles and soils, to provide a better understanding of what is involved and to develop more precise and comprehensive mathematical models of it.

Such an approach has been pursued for some time and has brought out two major aspects of the problem of vehicle operation on soft soils. One is the

generation of thrust, or tractive effort, to propel a vehicle. The other is the resistance to motion due to the deformation of the soil by vehicles.

The generation of thrust is accompanied by shearing of the soil under the vehicle and tractive effort was consequently related by E W E Micklethwaite to Coulomb's equation for the shear strength of soils, that is for the maximum shear stress which can be imposed on soils before they fail by shearing:

$$\tau_{max} = c + \sigma \tan \varphi \qquad \text{14.9}$$

where τ_{max} = maximum shear stress
c = cohesion of soil
σ = stress normal to sheared surface
φ = angle of internal shearing resistance

The outcome of applying Coulomb's equation has been the following expression for the maximum possible tractive effort F_T (14.21):

$$F_T = A\ c + W \tan \varphi \qquad \text{14.10}$$

where A is the area of contact between the vehicle and the soil and W is the weight of the vehicle, as before.

In frictional soil, such as dry sand, $c = o$ and in that case the maximum tractive effort depends only on the weight of the vehicle and the angle φ, which is approximately 35°. In consequence, the maximum tractive effort which a vehicle can develop on dry sand is, according to equation, 14.10, approximately 0.7 times its weight. On the other hand in a cohesive soil, such as saturated clay, φ – 0, which makes the maximum tractive effort dependent on the area of the tracks in contact with the soil and independent of the weight of the vehicle.

Equation 14.10 is based on the assumption that the weight of the vehicle is uniformly distributed over the contact area and also that the shear stresses along its length are all at their maximum, which may be true when track slip is 100 per cent but not in general. To cater for the variation of tractive effort with slip, M G Bekker modified equation 14.9 to include in it slip after observing that curves of shear stress versus shear deformation resembled those of displacements in heavily damped vibrations and, in effect, multiplied τ_{max} by their form function (14.22). This led to empirical equations for the shear stress τ as a function of slip s which could be integrated over the length of the contact area to produce expressions for the gross tractive effort at any slip, the most common of them being:

$$\tau = (c + \sigma \tan \varphi)\,(1 - e^{-sx/K}) \qquad \text{14.11}$$

where x is the distance from the front edge of the area of contact between the track and the ground and K is a constant dependent on the soil. Equation 14.9 has also been modified to include non-uniform distributions of normal pressure along the contact area.

Given equations for the gross tractive effort, what is then needed are expressions for the resistance to motion due to the deformation of the soil, so that this can be subtracted from the gross tractive effort to obtain the net tractive effort, or drawbar pull.

The most obvious forms of this deformation are the ruts created by the sinkage of the tracks into the soil and the work done in making them was taken to be the

cause of the resistance to motion on soft soils as early as 1913 (14.23). This was done by R Bernstein who also adopted a relationship between the pressure exerted on the soil and the resulting sinkage, from which the work done in forming the ruts could be calculated. The relationship was of the following simple form:

$$p = k \; z^n \qquad \text{.......... } 14.12$$

where p is the pressure, z is the sinkage and k is a coefficient dependent on the properties of the soil as is the exponent n, which Bernstein took to be equal to 0.5. Subsequently others also used this kind of empirical relationship with the value of n frequently taken to be 1. However, k was found to vary not only with the soil but also with the shape of the area on which the pressure acted and in particular with the width, the smaller dimension of the rectangular plates used in sinkage tests. In consequence, k could not be used as a soil constant which limited the usefulness of the pressure-sinkage relationship represented by equation 14.12.

To overcome its limitations, Bekker combined equation 14.12 with another empirical relationship which was used in civil engineering and in the mid-1950s produced the following pressure-sinkage relationship (14.24):

$$p = \left(\frac{k_c}{b} + k_\varphi \right) z^n \qquad \text{.......... } 14.13$$

where b is the smaller dimension of the loading plate and k_c and k_φ, as well as n, are soil constants determined by experiment and substantially independent of the shape of the loading area. But, unfortunately, their dimensions vary with n. This, together with other shortcomings of equation 14.13, led to an alternative being proposed which was similar in form but in which the soil constants were dimensionless and which had a theoretical basis instead of being purely empirical (14.25). In spite of this, equation 14.13 has been widely used to calculate sinkage and the resistance to motion due to the compaction of the soil F_R, which is given by:

$$F_R = b \int_0^{z_0} p \; dz \qquad \text{.......... } 14.14$$

where z_0 is the depth of the rut and b is now the width of the rut and of the track. Once F_R is determined, and assuming that there are no other forces resisting motion, the net traction or drawbar pull F_D is obtained by subtracting F_R from the gross traction F_T given by equation 14.10, or from the integration of equation 14.11, that is:

$$F_D = F_T - F_R \qquad \text{.......... } 14.15$$

However, compaction of the soil is not the only cause of the resistance to motion and equation 14.14 is generally a gross underestimate of it, which leads to overestimates of the net traction when it is used by itself to calculate the resistance. Moreover, the superposition of solutions obtained separately for the gross tractive effort and for the resistance to motion is questionable. It is particularly questionable in view of the fact that soil under the tracks is not subjected separately to normal and shear stresses but has them applied simultaneously, which means that

it is more highly stressed than under the plates used in sinkage tests. In consequence, the sinkage of the tracks and the resistance to motion due to it are greater in practice than those predicted on the basis of plate tests.

To account for the fact that the compaction of the soil which takes place when ruts are formed is not the only cause of the resistance to motion additional terms, representing the resistance due to the other causes, have been introduced into equation 14.15 (14.26). This has led to more realistic values of the resistance and further elaboration of the expressions for tractive effort and for the resistance to motion, which has been made to take into account the non-uniformity of pressure along the track and the effect on soil properties of the repetitive loading applied by consecutive road wheels. As a result, calculated values of the drawbar pull and of the pressure under the tracks have come to agree closely with experimental observations, in some soils at least (14.27).

What is more, even if some aspects of the semi-empirical approach are open to criticism, the quantitative relationships which it has produced represent an advance in several respects on the purely empirical methods. In particular, although it has often failed to produce accurate predictions of vehicle performance, the semi-empirical approach has thrown some very valuable light on the nature of the interaction between vehicles and soils.

There is a potential alternative to the semi-empirical approach which is based on the plasticity theory of soils and which is analytically more rigorous (14.28). But it involves complicated numerical solutions of problems which have to be formulated in terms of computer programmes and there are considerable difficulties about its application in practice.

14.6 References

14.1 *Automotive Suspensions* AMCP 706-356, US Army Materiel Command, Washington, 1967, pp.7-1 to 7-21.

14.2 A Stern. *Tanks 1914-1918*, Hodder and Stoughton, London, 1919, pp.258-274.

14.3 E H Tennyson d'Eyncourt, 'Account of the British Tanks used in the War', *Engineering*, Vol.108, No.2803, 19 September 1919, pp.371-374.

14.4 E H Tennyson d'Eyncourt, op.cit., p.375.

14.5 F Heigl. *Taschenbuch der Tanks*, Lehmanns Verlag, Munich, 1926, p.17.

14.6 H E Merritt, *Some Considerations Influencing the Design of High-Speed Track Vehicles*, Proc. Inst. Automobile Engineers, Vol.33, 1938-39, pp.399-402.

14.7 N I Gruzdev, *Tanki-Teoria*, NKTM SSRM, Moscow, 1944.

14.8 D Rowland, *Tracked Vehicle Ground Pressure and its Effect on Soft Ground Performance*, Proc. 4th Int. Conf., Int. Soc. Terrain-Vehicle Systems, Stockholm, 1972.

14.9 D Rowland, *A Review of Vehicle Design for Soft Ground Operation*, Proc. 5th Int. Conf., Int. Soc. Terrain-Vechicle Systems, Detroit 1975.

14.10 J F C Fuller, *Tanks in the Great War*, John Murray, London, 1920, p.105.

14.11 F Mitchell, *Tank Warfare*, Thomas Nelson, London, c.1934, p.24.

14.12 S J Knight and A A Rula, Measurement and Estimation of the Trafficability of Fine-Grained Soils, *Proc. 1st Int. Conf. on the Mechanics of Soil Vehicle Systems*, Edizioni Minerva Tecnica, Turin, 1961, pp.371-384.

14.13 E G McKibben and D O Hull, 'Soil Penetration Tests as a Means of Predicting Soil Resistance', *Agricultural Engineering*, No.6, 1940.

14.14 S J Knight et al., op.cit., pp.381-382.

14.15 D R Freitag, *A Dimensional Analysis of the Performance of Pneumatic Tires on Soft Soils*, Tech. Rep. No.3-688, WES, Vicksburg, 1965.

14.16 G W Turnage, *Performance of Soils under Track Loads*, Report 2, WES, Vicksburg, 1971.

14.17 A A Rula and C J Nuttall, *An Analysis of Ground Mobility Models*, Tech. Rep. M-71-4, WES, Vicksburg, 1972.
14.18 D Rowland and J W Peel, *Soft Ground Performance Prediction and Assessment for Wheeled and Tracked Vehicles*, Proc. Conf. on Off-highway Vehicles, Tractors and Equipment, Inst. Mech. Eng., London, 1975, p.88.
14.19 D Rowland, op.cit., Stockholm, 1972
14.20 D Rowland and J W Peel, op.cit., p.88.
14.21 E W E Micklethwaite, *Soil Mechanics in Relation to Fighting Vehicles*, Military College of Science, Chertsey, 1944.
14.22 M G Bekker, *Theory of Land Locomotion*, University of Michigan Press, Ann Arbor, 1956, pp.263-271.
14.23 R Bernstein, 'Probleme zur Experimentellen Motorflugmechanik,' *Der Motorwagen*, No.16, 1913.
14.24 M G Bekker, *Off-the-Road Locomotion*, University of Michigan Press, Ann Arbor, 1960, pp.32-34.
14.25 A R Reece, *Principles of Soil-Vehicle Mechanics*, Proc. Auto. Div., Inst. Mech. Engrs., Vol.180, Part 2A, 1965-66.
14.26 M G Bekker, *Introduction to Terrain-Vehicle Systems*, University of Michigan Press, Ann Arbor, 1969, pp.482-491.
14.27 J Y Wong, M Garber and J Preston-Thomas, *Theoretical Prediction and Experimental Substantiation of the Ground Pressure Distribution and Tractive Performance of Tracked Vehicles*, Proc. Inst. Mech. Engrs., Vol.198D, No.15, 1984.
14.28 L L Karafiath and E A Nowatzki, *Soil Mechanics for Off-Road Vehicle Engineering*, TransTech Publications, Rockport, 1966.

Chapter 15

Armour Protection

15.1 Steel Armour

Armour protection governs to a large extent the ability of tanks to survive under fire and, to the extent that it makes them immune to a number of enemy weapons, enables them to move more freely on the battlefield. It is, therefore, an important attribute of tanks and one to which much attention has been given, often at the expense of their other characteristics.

For the first 40 years of their development the armour of tanks was designed almost only to protect them against ballistic attack and consisted solely of high strength steels. The steels have contained between 0.25 and 0.4 per cent of carbon and various alloying elements, the principal ones being nickel and chromium, the amounts of which have ranged from 0.5 to 3.75 and 1.8 per cent, respectively. The tensile strength of steel armour has also varied, from 850 to 1700 MN/m^2, but even at its lowest it has been considerably higher than that of ordinary low carbon steel, which is about 350 MN/m^2.

Steel armour is heat treated, which involves hardening it in order to increase its resistance to penetration by projectiles and then tempering it to make it tougher and therefore better able to absorb the kinetic energy of the impacting projectiles, even though this reduces its hardness somewhat. The relatively thin, 8 to 14mm plates of steel armour used in the tanks of the First World War were heat treated to a Brinell Hardness Number (BHN) ranging from 420 to as much as 650 (15.1). But, as plates became thicker and were joined by welding instead of being riveted on to an angle iron framework, armour had to be less hard. Thus, from the 1930s onwards, armour plates became generally of machineable quality steel with a hardness ranging from about 390 BHN for thin plates to 280, or even 220 BHN for very thick plates. Relatively thin plates have also had a hardness of only 260 BHN when used for belly armour, which has to withstand mine blast instead of attack by projectiles and which needs therefore to be tough rather than hard.

During the mid-1930s the thickness of plates was, typically, still not more than 15mm but it increased rapidly with the outbreak of the Second World War. Thus, tanks such as the Soviet KV of 1941 had plates 75mm thick and the German Tiger II of 1944 had a 150mm plate at the front of its hull and a 185mm plate at the front of its turret. An even thicker, 250mm plate formed the front of the superstructure of the Jagdtiger, the 128mm gun tank destroyer based on the Tiger II chassis which, at 71.7 tons, was the heaviest armoured fighting vehicle used by the end of the Second World War.

Fig. 15.1 German Jagdtiger, the heaviest and most heavily armoured vehicle used during the Second World War which had a superstructure front plate 250mm thick.

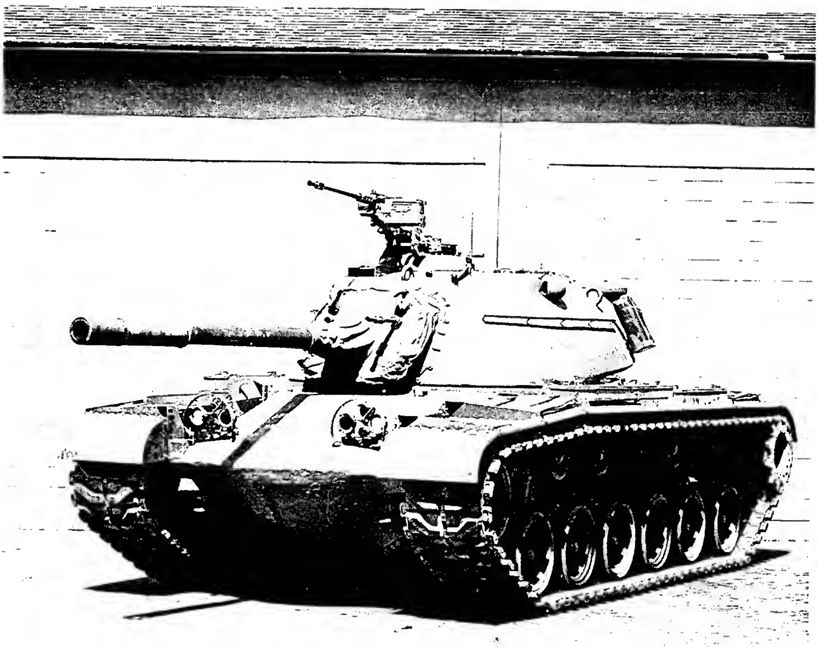


Fig. 15.2 Prototype of the US M48 tank with a one-piece cast hull and turret.

No plates as thick as that of the Jagdtiger appear to have been used since 1945. Machineable rolled homogeneous armour, or RHA, continued to be widely used but its maximum thickness was exemplified by the 100mm plates which have formed the fronts of the hulls of Soviet tanks from the T-54 to the T-62. Even the heaviest tank to be built before the advent of other types of armour, the 66 ton Conqueror of the late 1950s, had RHA plates no thicker than 125mm at the front of its hull.

Cast armour was introduced on a limited scale during the First World War, when some of the turrets of the Renault FT light tanks were made by casting instead of being fabricated from rolled plates. One-man cast turrets were subsequently fitted to other French tanks and by 1941 larger cast turrets were being used on British, Soviet and US tanks. After the Second World War the use of cast armour spread to almost all battle tank turrets but the thinner-walled turrets of light tanks continued to be fabricated from rolled plates.

During the 1930s the use of cast armour also began to spread to hulls and in particular to the hulls of French light tanks, such as the R-35 and H-35, which were the first to be made out of large castings. In 1941 castings began to be used on a large scale for the production of hulls of the US M4 medium tanks and they were subsequently incorporated in the hulls of other tanks, such as the US M26 and M46 medium tanks, the Soviet IS and British Chieftain, particularly in the form of cast glacis. By the 1950s complete hulls began to be cast in one piece for the US M48 tanks and hulls were similarly cast for the Swiss Pz.61 and Pz.68 tanks as well as the US M60 and M103 tanks.

The chemical composition of cast armour has been much the same as that of rolled armour plates but its quality is inherently more variable and the thickness of castings can not be controlled as accurately as that of rolled plates, which requires them to be somewhat thicker to allow for it. Castings are also at a disadvantage in relation to plates because they are generally of complex shape and varying thickness and can not, therefore, be given equally uniform heat treatment, which has an adverse effect on their ballistic properties. In consequence, cast armour needs to be about 5 per cent thicker than RHA for a given level of ballistic protection.

On the other hand, casting lends itself much more readily than fabrication from rolled plates to the production of the complex shapes of turrets and hull fronts. It also facilitates an efficient distribution of armour, as well as allowing a reduction in the number of welded joints and in the preparation that goes with them. The ultimate demonstration of this is provided by the turrets and the hulls which have been cast in one piece. However, the size of the castings which they represent is apt to tax industrial resources.

In principle, the ballistic protection provided by RHA and by cast armour can be improved upon by steel armour which is much harder than they are and is therefore better able to resist penetration by projectiles but which is still tough, so that it does not shatter under their impact. Armour of this kind has generally had the increased hardness confined to its outer face or layer. This has avoided the problem of armour becoming brittle due to a high degree of hardening as most of it remained relatively soft and therefore tough.

An early example of it was the face-hardened armour of which tanks produced by Vickers-Armstrongs during the 1920s and 1930s were normally made. This had a carburised face which contained up to 1.8 per cent of carbon and had a hardness of about 600 BHN, while its softer rear face had a hardness of 400 BHN. It was produced in the form of plates up to 20mm thick and was very effective against the contemporary armour piercing projectiles. But it was virtually unmachineable and

unweldable after the heat treatment, so that it could only be assembled by being bolted or riveted on to a frame (15.2). This, together with the difficulty of producing it in quantity and its cost led to its use being abandoned at the outbreak of the Second World War.

Some armour face-hardened to more than 400 BHN was used on German tanks in 1942 in the form of 20mm thick applique plates fitted to a number of Pz.Kpfw.III. They proved effective against the solid armour-piercing shot fired by the contemporary British 40mm tank guns but they represented the only significant use of face-hardened armour during the Second World War.

There has been no further use of face-hardened armour but since the 1960s there has been a revival in the use of homogeneous high hardness armour, which was in effect the type of armour used in British tanks during the First World War. Its renewed use started with Cadillac Gage Commando armoured cars first built in 1963 in the United States and during the 1970s spread to other light armoured vehicles.

The new generation of homogeneous high hardness armour consisted originally of low alloy steels heat treated to about 500 BHN. Plates made of them were at first prone to crack when welded into hulls, even without being exposed to ballistic attack, because of their brittleness and the stresses set up in them by heat treatment and welding. However, improvements in the composition and processing of high hardness armour overcame the problem of cracking and it has been successfully used in light armoured vehicles where its hardness of 500 to 550 BHN made it more effective than RHA against armour piercing as well as ordinary bullets. For instance, 12.5mm of high hardness armour has been sufficient to defeat 7.62mm NATO AP ammunition at point blank range and normal impact compared with 14.5mm of RHA of between 320 and 380 BHN. This meant that the latter was 16 per cent heavier for the given level of protection.

The 1960s also saw a revival of interest in dual-hardness armour. This consists of layers of two different steels bonded together. It first appeared in Britain well

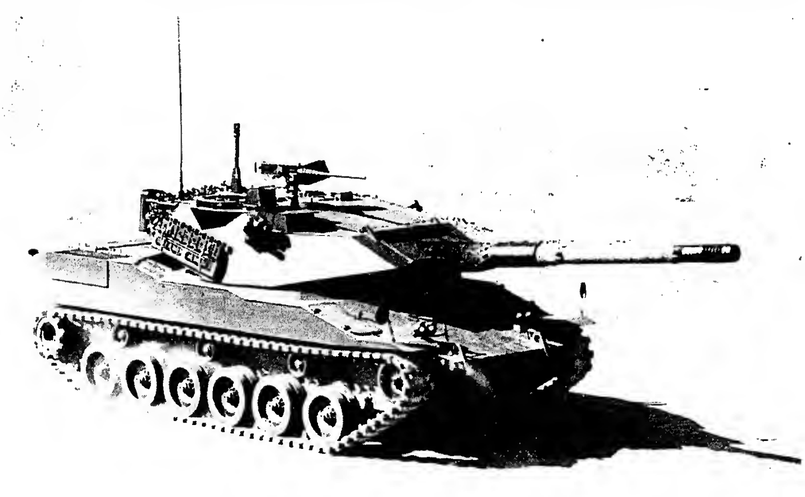


Fig. 15.3 Cadillac Gage Stingray light tank with a hull and turret of high hardness steel armour. (Cadillac Gage Textron)

before the Second World War in the form of Hadfield Duplex armour but it only came into use in the 1970s with its adoption for the wheeled armoured vehicles produced in Brazil by Engesa. The outer layer of dual-hardness armour has a relatively high carbon content and after heat treatment its hardness rises to more than 600 BHN, while the backing layer has a lower carbon content and is softer and more ductile. This makes the backing layer better able to absorb the energy of the impacting projectiles and, given a strong metallurgical bond, it can arrest the propagation of cracks in the hard outer layer, which is very effective otherwise in resisting penetration. As a result, dual-hardness armour is even more effective than homogeneous high hardness armour. For instance, it needs to be only 9mm thick to defeat 7.62mm NATO AP ammunition under the conditions mentioned previously, which makes it 28 per cent lighter than high hardness armour and 38 per cent lighter than RHA.

For a time the use of high hardness and dual-hardness armour was confined to relatively thin plates, their maximum thickness being of the order of 25mm and most being considerably thinner than this. This made them applicable only to light tanks and other light armoured vehicles. However, by the mid-1980s the thickness of high hardness plates increased to 50mm and that of dual-hardness plates to 100mm, making them suitable for heavier armoured vehicles.

In the meantime improvements in the metallurgical quality of steels led to new types of armour which could be produced in the form of relatively thick plates and which could be heat treated to higher levels of hardness than RHA or cast armour without undue loss of toughness because of their microcleanliness and more uniform properties. An early example of this was the High Performance Armour developed in the United States and incorporated in the mid-1960s in the design of the MBT-70. The High Performance Armour contained 9 per cent of nickel and 4 per cent of cobalt and was produced by vacuum arc remelting. It was heat treated to 500 BHN, like the other types of high hardness armour, but it was produced from the start in the form of plates 40mm thick.

Other vacuum melted steels of the maraging type contain as much as 18 per cent of nickel and 10 per cent of cobalt and have been heat treated to 590 BHN. Thin plates of this type of armour need to be only 9mm thick to defeat 7.62mm NATO AP ammunition under the same conditions as those mentioned previously, which makes it comparable in this respect with dual-hardness armour. However, its cost has been very high and little if any use appears to have been made of it.

No use appears to have been made also of unidirectionally solidified steel armour which was developed in the United States during the 1960s. This was based on less expensive, high carbon steels of the 4350 type and exhibited very good ballistic properties when heat treated to about 550 BHN. But it did not lend itself to the production of large ingots and the idea of making armour plates out of it was abandoned (15.3).

In contrast, considerable attention has been given since the 1960s to electroslag remelted, or ESR, steels which have come to be considered most suitable for the production of thick plates of homogeneous high hardness armour. ESR armour has been based on the widely used 4340 type of steel, which contains 0.4 per cent of carbon and, in contrast to some of the earlier armours produced by remelting, only 1.7 per cent of nickel and 0.8 per cent of chrome. Moreover, the metallurgical quality of steel produced by electroslag remelting is even better than that of steels made by other remelting processes and it costs less.

Typical armour of 4340 ESR steel has a tensile strength of 2190 MN/m^2 and a

hardness of 550 BHN. But even when heat treated to this high level of hardness it still possesses considerable ductility and toughness. In consequence, it is not only effective in resisting penetration by projectiles but its use virtually eliminates the danger of scabbing, that is of large, lethal chunks of armour being thrown off the back of plates by stress waves caused by the explosion on them of HESH projectiles. The use of it also greatly reduces spalling when armour is perforated by an overmatching projectile, that is the breaking up of the armour to form a conical spray of small fragments which increase the damage caused by the projectile. The use of the ESR armour also eliminates the risk of spall fragments being thrown off by partial penetrations.

15.2 Configuration of Armour

Whatever its kind, the amount of armour with which vehicles can be provided is governed by their weight. Thus, the lightest of them can only have enough armour to protect them against the lowest level of attack, which is represented by rifle calibre bullets and by shell fragments. This form of attack is likely to come from almost any direction and its probability distribution in the horizontal plane is consequently assumed to be circular, which calls for equal protection all round. In fact, such protection is just about all that can be had when the armour of a vehicle is restricted to the minimum necessary to keep out rifle bullets and shell fragments. This amount of armour also corresponds to the minimum of metal required by the body of a vehicle for structural reasons.

Examples of vehicles with the minimum amounts of armour have been provided in the past by light tanks and more recently by scout cars. However, most armoured vehicles have had more than the minimum of armour protection and tanks in particular have been provided with progressively greater amounts of armour in response to the increases in the level of the threat facing them. But the provision of more armour inevitably results in increases in weight and this sets severe limits to the total amount of it that particular types of vehicles can have. Given such limits what armour vehicles can have needs to be used as effectively as possible and this involves a recognition of the fact that the forms of attack against which the heavier armour is intended are much more likely to come from the front than from the sides or the rear. It is far less effective therefore to increase armour protection evenly all round than to distribute it so that there is much more of it over the front of vehicles, where the probability of attack is greatest, than at the sides where a lower level of protection is acceptable because of the lower probability of attack.

Thus, light armoured carriers are generally designed so that their frontal armour can resist 12.7mm armour piercing bullets fired at short range but their sides are only protected against 7.62mm AP bullets. Similarly, light tanks have been designed in recent years to be immune over their front to 14.5mm AP projectiles fired at short range but at their sides they have only had enough armour to resist 12.7mm AP bullets. Battle tanks have had much heavier armour but also unequally distributed, their frontal armour commonly corresponding to that required to defeat the armour piercing projectiles of their own guns while their side armour has only been capable of resisting considerably lower levels of attack.

At first the armour of tanks was distributed on a purely intuitive basis but since the Second World War the directional variation of the probability of attack has been the subject of considerable analysis. As a result, the distribution of the probability of attack and of the armour matching it has been placed on a

quantitative basis.

The first of the studies to produce a distribution of the probability of attack appears to have been carried out in 1943 in Britain by J M Whittaker and was based on a tank advancing against a line of anti-tank guns (15.4). Although it was entirely theoretical Whittaker's distribution proved to be in keeping with the record of hits sustained by tanks during the Second World War and has been used since then as the basis of distributing armour. In particular, it has led to the concentration of design effort on making tanks immune to attacks coming over a frontal arc of 60°, since it showed that 45 per cent of all of them were likely to fall within this arc.

There have been arguments that in mobile warfare the distribution of the probability of attack is likely to be more uniform than that indicated by Whittaker's analysis or the cardioid and the elliptical distributions produced by other studies. On the other hand, it has been argued with no less conviction that the increasing range of engagements, made possible by more powerful tank guns and anti-tank weapons, was likely to result in more attacks being concentrated over the frontal arc. In fact, some studies have suggested that as many as 70 per cent, or more, of the attacks would be within the arc of 60°. However, analysis of tanks hit during the Arab-Israeli wars of the 1960s and 1970s, which provide the most recent evidence, gave the probability of attack within the frontal arc of 60° as 0.49, which is not very different from Whittaker's analysis and the Second World War data.

To increase the effectiveness of armour and in particular of the frontal armour, the original, vertical arrangement of nose, superstructure and turret plates was generally abandoned during the Second World War in favour of sloped armour. When well sloped, that is inclined at more than about 65° from the vertical, armour offered the advantage of causing some projectiles to ricochet, or to shatter, and of being able to avoid being perforated even when relatively thin. Very highly sloped armour has also degraded the performance of some shaped charge warheads by interfering with the symmetry of the collapse of their liners into jets.

Sloping of armour to a lesser degree also makes it more effective against most kinetic energy projectiles, because this causes it to offer resistance to penetration which is non-symmetrical and, therefore, deflects projectiles from going straight through the armour into a longer path. However, the advantages of sloping armour are small, if any, when it is inclined at less than 10 or 20 degrees from the vertical (15.5). This and the general effectiveness of sloped armour is illustrated in Fig.15.4 in terms of the ratio of its effective or equivalent thickness to the actual shot-line thickness and the angle of inclination from the vertical.

In contrast, sloping of the armour makes generally no difference to the penetration of it by the jets of shaped charge warheads, except for the interference in some cases with the formation of the jet mentioned previously. There is therefore little to be gained by it in their case. This is true even though the sloped armour can be less thick for protection against a particular size of shaped charge, because the thickness in the path of the jet has to be the same whether the armour is sloped or not. Consequently, its weight per unit of the vertical area to be protected does not vary with the slope of the armour. The long-rod penetrators of APFSDS projectiles are similarly unaffected by the slope of the armour.

Another approach to making armour more effective through changes in its configuration consists of arranging it in the form of two layers separated from each other by a certain distance. Spaced armour of this kind was introduced in 1942 to increase the protection of the German Pz.Kpfw.III tanks and was an alternative to

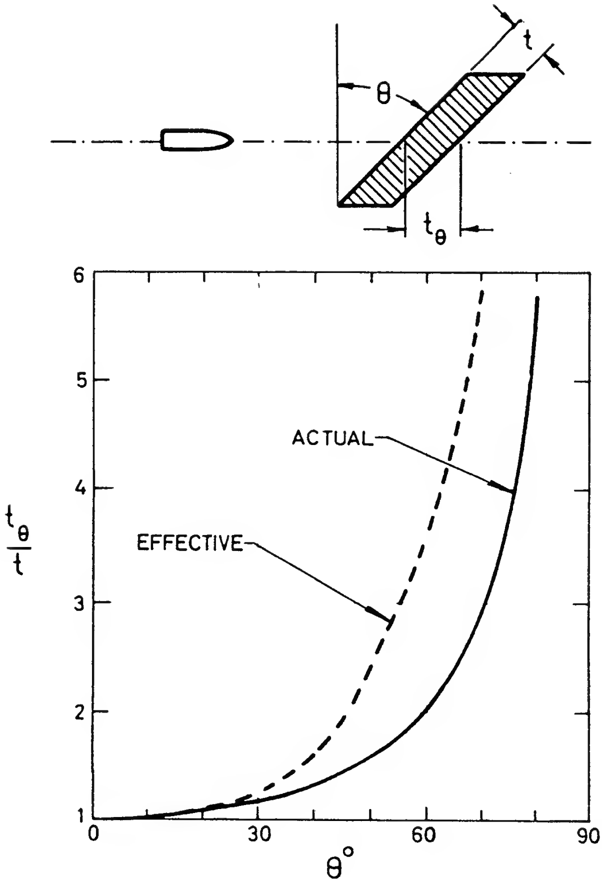


Fig. 15.4 Effect of inclining armour plate on its horizontal thickness.

the applique armour which was bolted directly to the hull superstructures of the Pz.Kpfw.III and IV in 1940 and 1941. Subsequently similar applique armour was also welded on the turrets and hulls of Soviet T-34 Model B, US M4 medium tanks and British Churchill IX and XI tanks.

Apart from being located 100 to 120mm in front of the main armour, some of the 20mm plates added to the Pz.Kpfw.III were face-hardened to about 430 BHN, which made them more effective against armour piercing projectiles than if they had been of standard armour with a BHN of 350, or so. Otherwise spaced armour offered the possibility of its outer plate stripping off the ballistic cap of armour piercing projectiles or of deflecting them and therefore making them less well able to penetrate the inner plate. However, spaced armour was not considered to offer sufficiently better protection against the contemporary kinetic energy projectiles to justify the complication in the construction of tanks which its use entailed. In

consequence, the example of the Pz.Kpfw.III was not followed until the 1960s, when a spaced form of additional armour was fitted in the United States to the XM765 derivative of the M113 armoured personnel carrier. Subsequently a similar type of spaced armour was adopted for other light armoured vehicles, including the US M2 Infantry Fighting Vehicle. Other forms of spaced armour were also added during the mid-1970s to the Leopard 1A1 tanks of the German Army and then to Soviet T-55 and T-62 tanks.

What is more, thick spaced armour was incorporated from the start in the design of the US-German MBT-70 of the 1960s and then in the Israeli Merkava. But during the 1970s the use of two spaced layers of thick armour was overtaken by the development of more effective multi-layered configurations.

In the meantime a different type of spaced armour had appeared in the form of the additional plates fitted in 1943 to the sides of the German assault guns. The plates were only 5 or 8mm thick and of mild steel but they provided additional protection against the contemporary shaped charge warheads by causing them to detonate away from the main armour and thereby reducing their effectiveness. Because their function was to set off shaped charges, the mild steel plates were even replaced by heavy gauge wire mesh on the Pz.Kpfw.IV Model J.

The use of thin skirting plates at the sides of tanks was continued after the Second World War with their adoption on the British Centurions and during the 1960s and 1970s it spread to several other tanks. They were regarded mainly as additional protection against the anti-tank rocket launchers and other infantry anti-tank weapons with shaped charge warheads which had come to be used on a large scale. But as shaped charge weapons were developed the stand-off distance at which their penetration was greatest increased and became equal to or greater than the distance at which the skirting plates were located away from the main armour. As a result, instead of degrading the performance of shaped charges as they did originally, the skirting plates could even make them more effective if they were struck at or close to normal. But if they were struck at an acute angle the oblique distance between them and the hull armour could still be sufficiently great to reduce significantly the penetration of shaped charges.

Spaced armour has also been used since the 1960s in the form of rows of high strength steel bars located in front of the main armour or of chains hung in front of it. So far as shaped charge weapons are concerned the effect of bar armour and of chains is similar, in general, to that of skirting plates but they can also degrade the performance of the smaller shaped charge rockets or grenades with simple fuzes by deforming their warheads before the fuzes are initiated. Bar armour can also deflect kinetic energy projectiles and consequently make them strike the main armour at a less effective angle while its weight is less than that of the equivalent armour plates. Similar results can be achieved against small calibre armour piercing projectiles by the use of plates with a random pattern of small holes which make them lighter than equivalent solid plates. Perforated plates of this kind were adopted during the 1980s to improve the protection of some armoured carriers.

Another departure from the conventional, single layer configuration of armour consists of the use of horizontal ribs welded on the glacis plates. Ribbed armour of this kind was first adopted on the Swedish S-tank and its ribs deflect some types of kinetic energy projectiles so that they turn away from the glacis plate and therefore strike it at even greater obliquity. Otherwise the ribs prevent small projectiles ricocheting off the glacis plate into the sights which may be above it.

No matter how effective the armour might be, some projectiles and missiles will

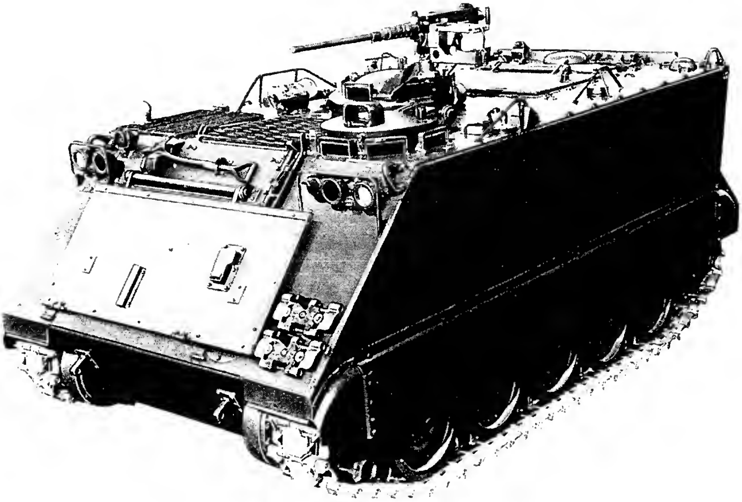


Fig. 15.5 US M113 personnel carrier, the first vehicle to be produced with aluminium armour. (FMC Corp.)

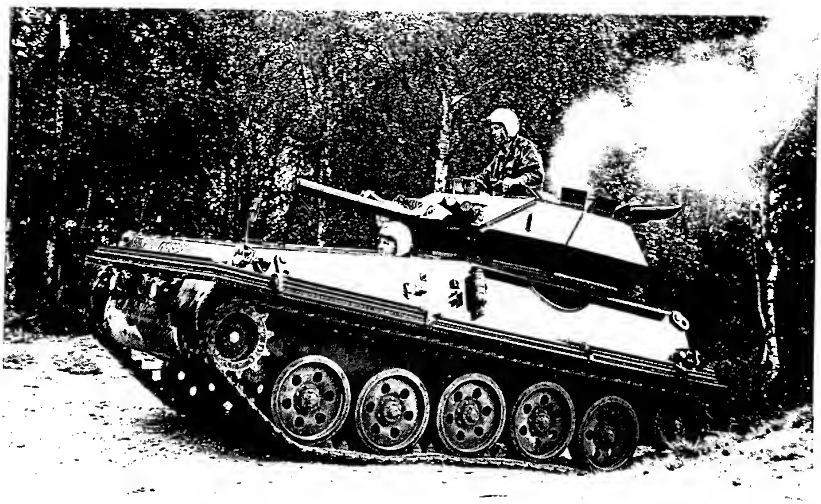


Fig. 15.6 Prototype of Alvis Scorpion light tank with a turret as well as hull of aluminium armour. (Alvis)

always perforate it but the damage caused by them behind the armour can be reduced by spall liners. These are fitted on the inside of the armour and consist typically of laminates of resin-bonded glass or aramid fibres such as Kevlar which reduce the angle of the cone of high velocity spall fragments created by a perforation and, consequently, the damage caused by it. Similar results can be obtained by a thin inner shield of steel located away from the armour but its effectiveness, like that of the liners made of laminates, is constrained by the limited volume which can be devoted to them within tanks.

Liners of appropriate materials can also increase the protection which the armour of tanks provides against the radiation resulting from the explosion of nuclear weapons. The radiation which is of concern consists of gamma rays and of neutrons. The steel armour of tanks provides a high degree of shielding against gamma rays because of its thickness and density. Thus, 18mm of armour can absorb approximately one half of the gamma radiation falling on it and since the armour of battle tanks is generally thicker than this the fraction of the radiation transmitted by it, which is called the transmission factor, is of the order of 0.1. An alternative and more commonly quoted measure of the effectiveness of shielding is the protection factor, which is the inverse of the transmission factor and which for battle tanks is appoximately equal to 10 (15.6).

Steel armour is less effective against neutrons and to absorb them other materials need to be added. These include hydrogenous materials, such as polyethylene, which slow down the neutrons, and elements with a high neutron capture cross section, such as boron. In consequence, polyethylene with a boron filler has been used to make liners which were originally introduced in the US-German MBT-70 to increase its protection against nuclear radiation.

Although they have been up to 50mm thick, radiological liners do not contribute to the ballistic protection of tanks because of the low density and low strength of the materials of which they are made. But they can be combined to some extent with spall liners.

15.3 Aluminium Armour

Until the 1950s the only material used for vehicle armour was steel. But since then an alternative to it has come into use in the form of aluminium armour.

Aluminium armour began to be developed in the United States where in 1956 the major producers of aluminium started to submit to the US Army samples of aluminium armour for firing trials. At about the same time FMC Corporation was awarded a contract for the development of a tracked armoured personnel carrier with an aluminium hull. As a result FMC built 31 aluminium as well as five steel hulls for trials and in 1959 received a contract for the production of the aluminium-hulled carrier, which became the M113 (15.7).

Since then the M113 has been produced on a large scale, becoming the most numerous armoured vehicle to be used outside the Soviet Union. Moreover, its development was followed by that of other aluminium armoured vehicles, such as the M114 reconnaissance vehicle, the 105mm M108 self-propelled howitzer and the 155mm M109 self-propelled gun, which has been produced in quantity not only for the US Army but also for several others.

The M113, M114, M108 and M109 formed the first generation of aluminium armoured vehicles with armour based on the 5083 type of alloy. This is an alloy of aluminium with about 4.5 per cent of magnesium and 0.75 per cent of manganese which has a tensile strength of 300 to 350 MN/m^2 and which is strain hardened to

improve its ballistic characteristics. Its hardness is only 75 BHN and this, together with its lower strength, means that plates of it have to be considerably thicker than those of steel armour for a given level of ballistic protection. For example, for protection against 7.62mm AP bullets at close range plates of 5083 aluminium armour have to be 48mm thick, compared with 14.5mm of conventional, rolled homogeneous steel armour of 380 BHN. Its density is only 2660 kg/m^3, compared with 7850 kg/m^3 of steel armour, but nevertheless the areal density of its plates, that is their mass per unit of area, is greater at 128 kg/m^2 than the areal density of 114 kg/m^2 of the RHA plates which provide the same protection against the hard-cored high velocity bullets.

However, when it comes to protection against the fragments of artillery shells, which constitute the principal threat to self-propelled guns and also a major threat to armoured carriers, the areal density of 5083 aluminium armour is significantly lower than that of RHA. In consequence, 5083 aluminium armour offers greater protection against shell fragments for a given weight, or the same protection as RHA for less weight.

Moreover, because 5083 aluminium armour has to be about three times as thick as RHA, plates of it are very much stiffer in bending in relation to their weight even if their areal density is about the same as that of ballistically equivalent RHA plates. This is the case in spite of aluminium being considerably less stiff than steel. In fact, the modulus of elasticity of aluminium is only 71 GN/m^2, compared with 206 GN/m^2 for steel armour. But the bending stiffness of plates is not only proportional to the modulus of elasticity but also to the cube of their thickness, which makes aluminium armour plates approximately nine times as stiff as steel plates of the same weight. In consequence, hulls of aluminium armour are more rigid than steel hulls of the same weight. This makes it possible to dispense with some of the structural stiffeners required in the construction of hulls, particularly of lightly armoured vehicles, and this saves weight. Thus, the aluminium hull of the M113 carrier is about 10 per cent lighter than its steel equivalent, which represents a saving of about 6 per cent in the total weight of the vehicle.

In addition to the savings in weight, aluminium armour is also easier to machine and the greater thickness of its plates makes it possible to use stepped joints, which provide a partial interlock between plates and require therefore less welding. All this has helped to reduce the cost of producing vehicles with aluminium armour but its cost per ton has been significantly higher than that of RHA.

The development of the original aluminium-magnesium-manganese alloys was followed by that of aluminium-zinc-magnesium alloys of the 7039 type, which were introduced during the 1960s in the second generation of aluminium-armoured vehicles. These included the US M551 Sheridan light tank, which had a hull of the 7039 alloy, although it still had a steel turret. Others were the British Alvis Scorpion light tank and the Fox wheeled armoured vehicle, both of which had turrets as well as hulls of aluminium armour, and the French AMX-10 tracked armoured infantry vehicle.

Alloys of the 7039 type contain 5 per cent of zinc and 2.5 per cent of magnesium and, in contrast to the earlier alloys, are heat treatable. They are also stronger, having a tensile strength of up to 485 MN/m^2, and harder, with up to about 150 BHN. As a result, they are superior ballistically and they do not need, therefore, to be as thick and as heavy as equivalent plates of 5083 armour. For instance plates of 7039 armour need to be only 38mm thick to provide protection against 7.62mm AP bullets at short range, which makes their areal density equal to 106 kg/m^3. This is significantly less than the areal density of equivalent 5083

armour, even though the density of the 7039 alloy is somewhat higher at 2780 kg/m^3. Their areal density is also lower than that of RHA but not of high hardness steel armour. The advantage of 7039 armour over other types of armour is even greater when it comes to some larger calibre AP projectiles. For example, in the case of 14.5mm AP projectiles its areal density is 26 per cent lower than that of RHA at normal impact, although not very different at high obliquities (15.8).

Inevitably, a price has had to be paid for the superior ballistic characteristics of the 7039 type alloys. This has been mainly in the form of welding problems, which have called for careful control of the heat input to safeguard against stress corrosion in the heat affected zone. The susceptibility of the 7039 alloys to corrosion stress cracking also made it necessary to cover exposed edges of plates with weld material and to avoid machining or the drilling of holes near weld joints.

But, in spite of the measures taken against it, corrosion stress cracking has been a major problem with the hulls and turrets welded from alloys of the 7039 type. In the case of vehicles of the AMX-10 series the problem has been minimised by the use of a 7020 alloy, which is somewhat less strong but which is more ductile and has a greater resistance to stress corrosion. However, in the case of the US LVTP7 amphibious carrier the problem was considered to be so serious that although its LVTPX12 prototypes were built during the late 1960s with 7039 armour this was abandoned in favour of a return to 5083 armour when it was put into production in the early 1970s. The aluminium armour of the US M2 Infantry Fighting Vehicle produced in quantity during the 1980s also consists almost entirely of the 5083 alloy, the use of the 7039 alloy being confined in it to a part of its superstructure and of the turret.

To compensate for its lower resistance to high velocity bullets, the 5083 armour of the M2 IFV, and of other aluminium armoured vehicles, has had thin plates of high hardness steel added to its outside. Such a combination of an outer layer of a hard material with an inner layer of a more ductile but tough material is very sound in principle and has proved effective in practice. For example, a combination of high hardness steel with the 5083 alloy capable of stopping 7.62mm AP bullets at close range has a lower areal density not only than 7039 armour but also high hardness steel armour by itself.

When aluminium armour began to be developed in the United States during the 1950s alloys of other non-ferrous metals were also investigated as possible armour materials. The most promising of these were titanium alloys and in particular an alloy containing 6 per cent of aluminium and 4 per cent of vanadium, which has a density of 4430 kg/m^3 and a tensile strength of 930 MN/m^2. On an areal density basis this Ti-6AL-4V alloy proved superior to aluminium armour and RHA as protection against AP bullets and to RHA in the case of shell fragments (15.9). At first it suffered from the disadvantage of back spalling under ballistic impact but this has been reduced considerably during the course of its development. However, the cost of titanium armour has remained much higher than that of aluminium as well as steel armour and this has confined its use to ground attack aircraft and helicopters.

15.4 Non-Metallic, Composite and Spaced Armour

The introduction of anti-tank munitions based on shaped charges which proved capable of perforating relatively thick monolithic steel armour led to research into the use of other materials and configurations of armour with the object of developing more effective protection against them.

The simplest model of the penetration of monolithic targets by shaped charge jets is based on the assumption that the process is of a hydrodynamic nature and leads to equation 4.16 quoted earlier. Using this equation it can be shown that the ratio of the penetration t_m and t_s of a shaped charge jet into a particular material and into steel, respectively, is equal to the square root of the inverse of their ratio of densities ρ_m and ρ_s, that is:

$$\frac{t_m}{t_s} = \sqrt{\frac{\rho_s}{\rho_m}} \qquad \text{15.1}$$

If the density of a particular material is lower than that of steel the penetration of the jet into it is obviously greater. But the areal density of it required to absorb the penetration, which is equal to $t_m\rho_m$, is lower than that of steel, the ratio of the areal densities being equal to the square root of the densities of the two materials:

$$\frac{t_s\,\rho_s}{t_m\,\rho_m} = \sqrt{\frac{\rho_s}{\rho_m}} \qquad \text{15.2}$$

This means that the mass of lower density materials required for protection against shaped charges is less than that of steel. Thus, in theory, the ratio of the areal density of RHA to that of a material like aluminium armour, which is usually called the mass effectiveness or the mass efficiency of the material in question, is about 1.7.

Polymeric materials, which are less dense than aluminium armour, are even better. For example, the mass efficiency of polymethyl-methacrylate, which has a density of 1180 kg/m^3, is 2.57. This ratio is, of course, purely theoretical but the superiority of lower density materials as protection against shaped charges is borne out in practice in many cases and some are not only as good but even better than their theoretical mass efficiency would suggest, polymethyl-methacrylate being one of them (15.10).

Similarly, some liquids are very effective, in relation to their mass, in resisting the penetration of shaped charge jets. One of them is diesel fuel which, typically, has a density of 820 kg/m^3. In theory, therefore, its mass efficiency is 3.09 but experiments show that in practice it can be more than that. This indicates that fuel cells can be used to increase significantly the protection of tanks against shaped charges, which has been done in some tanks built since the 1950s, including the Swedish S-tank and the Israeli Merkava.

But, although the mass of the protection provided by some low density materials against shaped charges is considerably lower than that of the equivalent steel armour, their thickness is much greater and generally impracticable. Moreover, no reasonable thickness of them can provide protection against kinetic energy projectiles. They can not, therefore, be used by themselves but they can be combined effectively with other, higher density materials.

Attempts to use low-density non-metallic materials to increase the protection of tanks against shaped charge weapons began towards the end of the Second World War in the United States. The most promising outcome of them was considered to be a mixture of quartz gravel and a mastic consisting of asphalt and wood known as HCR2. This was made into panels 250mm thick which were tried on some US

M4 medium tanks in 1945 but which were not used beyond firing trials (15.11).

During the 1950s two other forms of armour incorporating non-metallic materials were developed in the United States. One of them was siliceous cored armour which consisted of fused silica, typically 64mm thick, embedded in cast steel armour (15.12). It was to be used in improved versions of US M48 tanks and it was also incorporated in several US tank designs of the mid-1950s (15.13). It was considered as late as 1958 for the US M60 tank but the idea of using it was then abandoned, partly because of the difficulty and the cost of producing it.

The improvement in protection which it offered was also somewhat limited. The fuzed silica itself has a mass efficiency of about 3 but the overall mass efficiency of the armour incorporating it was only 1.4 and improvements of this order could be obtained more simply by changing from RHA to the high strength steel armour which began to be developed during the 1960s.

The other type of armour developed in the United States during the 1950s consisted of blocks of glass encased in steel. It was tried in the form of applique armour on M48 tanks and provided about the same degree of protection as the siliceous cored armour but again it was not adopted (15.14).

No composite armour appears to have been adopted for use in tanks until the appearance in 1971, in Britain, of the FV 4211 experimental tank with packs of the so-called Chobham armour, which had been developed during the 1960s at what was then the Fighting Vehicles Research and Development Establishment of the British Ministry of Defence. FV 4211 was, in effect, a Chieftain tank redesigned to demonstrate that tanks could incorporate Chobham armour, which offered much greater protection against shaped charge weapons than conventional steel armour.

In consequence, Chobham armour was adopted for the US XM1 tank prototypes which began to be developed in 1972 and a somewhat similar type of armour was adopted in 1974 for the German Leopard 2 AV prototype. Since then almost all new battle tanks have been built with some form of composite or multi-layered armour, instead of monolithic steel armour or of the two spaced layers of steel armour which were adopted in a few tanks during the 1960s and early 1970s.

Details of the armour used in the new tanks have been a closely guarded secret but the improvements in protection which they offer can be gauged from what is known about some of the materials and armour configuration which have been investigated since the 1950s. For instance, it is well known that very hard materials, such as ceramics as well as glass, offer considerably greater resistance to penetration by shaped charge jets than indicated, on the basis of their densities, by equation 15.1. This applies in particular to sintered aluminium oxide, or alumina (Al_2O_3), which has a tensile strength of about 200 to 270 MN/m^2 and is therefore considerably stronger than glass and more suitable for use as armour. The density of aluminium oxide, which ranges from about 3450 to 3600 kg/m^3, is greater than that of glass but, nevertheless, its mass efficiency is high. In fact, the mass efficiency of ceramics as well as glass ranges from about 2 to 3. High strength, ESR steels are also more effective against shaped charges than RHA, their mass efficiency being 1.4.

Aluminium oxide is still too brittle to be used by itself and has to be combined with steel or aluminium alloys to form layered or laminated armour. In its simplest form such armour consists of an outer layer of aluminium oxide tiles or blocks and an inner layer of steel or aluminium. Other, more sophisticated versions of it contain alternate layers of the ceramic and of metal.

Because it contains layers of steel or aluminium, the mass efficiency of lami-

Fig. 15.7 British FV 4211 experimental tank which was the first to be fitted with Chobham armour.

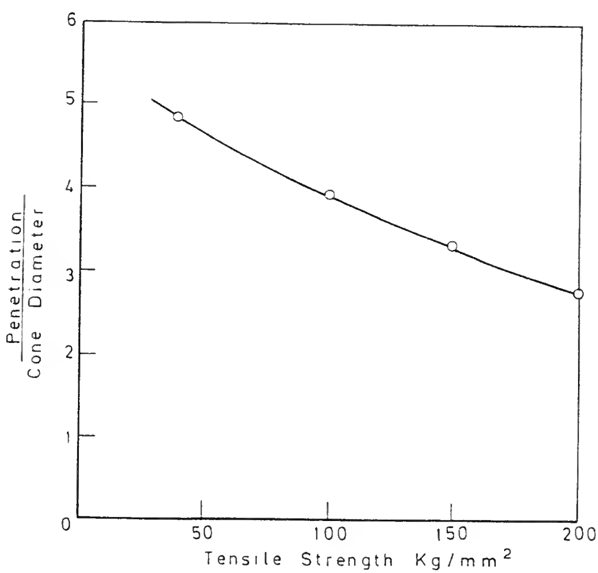


Fig. 15.8 Variation of shaped charge penetration with the strength of steel armour.

nated armour is not as high as that of the ceramics by themselves but it is still considerably more effective against shaped charges than monolithic RHA. For example, a composite consisting of a layer of aluminium oxide and a backing layer of high strength steel has proved to have a mass efficiency of 2.0. Another, consisting of layers of aluminium oxide, aluminium alloy and high strength steel has been shown to have a mass efficiency of 2.3 (15.15).

Similar results can be expected from other types of multi-layered armour containing alternate layers of metallic armour and of suitable non-metallic materials. Moreover, the effectiveness of multi-layered armour can be increased further by spacing its layers (15.16). Thus, even RHA can be made more effective against shaped charges by replacing single plates of it by arrays of spaced plates of the same total thickness.

Armour consisting of spaced layers is, inevitably, bulky. Its use increases therefore the overall dimensions of tanks, which is made evident by several tanks built since the early 1970s. This sets a limit to the amount of spacing that can be incorporated in multi-layered armour.

In addition to being effective in resisting the penetration of shaped charge jets, aluminium oxide is also very effective in relation to its weight against kinetic energy projectiles and in particular against small calibre armour piercing projectiles. This is in keeping with its high hardness, which in terms of the Vickers Hardness Number is 3000 whereas that of the hardest steel armour is about 700 and of RHA less than 400.

The ability of ceramics backed by a layer of aluminium or of a reinforced plastic to provide protection of considerably lower weight than equivalent steel armour began to attract attention in the United States in the 1960s and since then has been exploited in several different forms. One of the lightest of them consists of a combination of 8mm thick tiles of aluminium oxide with a 7mm thick backing of an aluminium alloy which can defeat 7.62mm NATO AP bullets at close range but

Fig. 15.9 Experimental version of the US M2 Infantry Fighting Vehicle with a hull of S-2 glass fibres bonded with a polyester resin. (FMC Corp.)

has an areal density of only 47 kg/m^2. This compares with the areal density of 114 kg/m^2 of the equivalent RHA mentioned earlier and implies a mass efficiency of 2.4.

Even better results have been obtained with boron carbide (B_4C), which has a hardness 35 per cent higher than aluminium oxide and a density of only 2480 kg/m^3. Thus, the 7.62mm AP bullets mentioned previously can be defeated by a combination of 7.4mm of boron carbide with a backing of an aluminium alloy which has an areal density of only 36 kg/m^2 and, consequently, a mass efficiency of 3.2 (15.17). However, the high cost of boron carbide has prevented its use in ground vehicles.

On the other hand, the use of aluminium oxide to increase the protection of light armoured vehicles against small calibre projectiles has been hampered by the difficulty of attaching ceramics to the metallic armour of vehicles or otherwise incorporating them in their construction. But this did not prevent tiles of aluminium oxide being successfully applied to the outside of the hulls of two experimental carriers built in 1985 for the US Marine Corps. The carriers were of the M113 type and their hulls were of sandwich construction with walls made up of inner and outer skins of resin-bonded E-glass fibres separated by a layer of closed-cell polyurethane foam.

The construction of the M113-type carriers with composite hulls was followed in 1989 by the construction by FMC Corporation of an experimental composite hull for the US Army for a larger vehicle of the M2 Infantry Fighting Vehicle type. This had solid walls of S-glass fibres, which are stronger than the commonly used E-glass fibres and which made up 68 per cent of the composite, by weight, the rest being accounted for by the polyester thermosetting resin matrix. To increase its ballistic protection, the vertical surfaces of the hull were covered with tiles of titanium diboride (TiB_2), which is superior ballistically to aluminium oxide in relation to its weight but which is more expensive. The combination of the polyester-bonded S-glass fibre composite with the titanium diboride tiles resulted in a hull which weighed 27 per cent less than the standard aluminium alloy armour hull of the M2A1 IFV.

Aluminium oxide in the form of relatively thick blocks has been incorporated also in armour systems intended to provide battle tanks with protection against kinetic energy projectiles fired by tank guns as well as shaped charge projectiles and missiles. Very little has been revealed about the effectiveness of such systems against large calibre kinetic energy projectiles but what has been published about them indicates that when it comes to attack by APFSDS projectiles their mass efficiency is at least 1.3.

15.5 Explosive Reactive Armour

In addition to laminate armour incorporating one or more layers of a non-metallic material and armour with spaced layers, the use of shaped charge weapons also inspired the development of an additional form of protection made up of modules with a layer of an explosive sandwiched between two metal plates (15.18). This form of protection was developed during the 1970s and has become known as explosive reactive armour. It was first used on the Centurion and M60A1 tanks of the Israeli forces during their operations in Lebanon in 1982 and a year or two later it also appeared on T-64 and then on other Soviet tanks.

Explosive reactive armour, or ERA, reduces the penetration capability of shaped charge jets by virtue of its explosive layer detonating when penetrated by a jet and

Fig. 15.10 M60A1 tank of the Israel Defence Forces with Blazer explosive reactive armour.

driving its plates apart, at about one tenth of the velocity of the jet. If the jet strikes the ERA sandwich at an angle new plate material is fed continuously into its path causing lateral disturbances which reduce its ability to penetrate armour located behind the ERA by 50 or even as much as 90 per cent.

The choice of the explosive which is sandwiched between the two metal plates is obviously most important as it must detonate when struck by a shaped charge jet but not when an ERA pack is struck by bullets or shell fragments. It should also not detonate due to a fire or field repairs involving welding. Detonation must also be confined to the module struck by a jet and not allowed to spread by sympathetic initiation to adjoining modules. Otherwise a single shaped charge hit would strip a tank of all its ERA, instead of depleting only one module.

As already implied, the ERA sandwich needs to be at an angle to the shaped charge jet to be effective. In fact, ERA is relatively ineffective until it is inclined at more than about 25 degrees from the normal to the jet but its effectiveness then increases with the angle of inclination (15.19).

The ERA sandwich must also be located some distance in front of the main armour to provide room for the movement of the back plate, which causes more perturbations to the jet than the front plate, even when the two are similar, as it moves in the same direction as the jet and this causes a greater mass of it to be involved with the jet (15.20).

Given the right arrangement of it, ERA can be very effective against shaped charges in relation to its mass. Typical examples of it consist of steel plates 3 or 5mm thick separated by 3mm of sheet explosive and have an areal density of 52 and 83kg/m^2. The Israeli Blazer ERA has had a slightly higher areal density of about 100 kg/m^2 but this is still no more than the areal density of steel armour 12.7mm thick. Yet it has a mass efficiency by itself of 20 to 24 against the shaped

charges of portable infantry anti-tank weapons. ERA can not, of course, be used by itself but only as an addition to other types of armour and combinations of the Blazer type with RHA have had an overall mass efficiency of 2.5 to 3.8 (15.21).

The mass efficiency of combinations of ERA with RHA inevitably varies, depending on the relationship between the areal density of the ERA and the penetration capability of the shaped charges. In practice it ranges from about 2 to 5, or more.

In principle ERA is effective not only against shaped charge jets but also against the long-rod penetrators of APFSDS projectiles. However, in that case its areal density needs to be considerably higher.

15.6 Active Protection Systems

The most elaborate form of protection to have been considered for tanks involves the use of sensor systems to detect the approach of an attacking projectile or missile and the firing of explosive charges or counter-missiles to destroy or disable it before it reaches its target. Protection of this kind has been called active or dynamic armour and it began to be considered, in the United States, in the mid-1950s.

One of the earliest forms of it was the Dash-Dot Device proposed in the United States at the Picatinny Arsenal which involved the use of a doppler radar to detect the approach of a projectile and the computing of its velocity to set off at the appropriate instant one of a bank of linear shaped charges to destroy it before it could strike its target (15.22). Another system proposed in the United States during the 1960s again involved the use of a doppler radar, to search for and to acquire attacking missiles, and the firing of weapons capable of exploding a cloud of fragments in the path of a missile to set off its warhead away from its target.

Radar has been the most frequently proposed basis for detecting attacking missiles and a radar missile detection system was actually tried on a US M60 tank during the 1960s. However, there are disadvantages to the use of radar for the active protection of tanks. One of them is the difficulty of detecting missiles against the background of noise which is generated when radar is used close to the ground. Radar systems are also active, which could make vehicles fitted with them easier to detect by the enemy. They can also be jammed and are relatively costly.

The alternative of detecting missiles by electro-optical means was explored in a system considered in Israel during the early 1980s (15.23). An electro-optical system has the advantage of being passive, and not vulnerable therefore to radiation homing missiles, as well as being less expensive than radar detection systems. But it relies for the detection of missiles on the thermal and optical signatures of the hot and luminous exhausts of their sustainer motors and can not, therefore, cope with missiles which, like the US TOW, do not use such motors but approach their targets in free flight. For similar reasons electro-optical systems can not detect free-falling submunitions or homing mortar bombs designed to attack tanks from above, which limits their usefulness.

Radar remains therefore the most promising basis for a detection system. In addition there has to be a control system containing a microprocessor to analyse the signals from the detection system to decide whether or when to fire whatever countermeasures are used. The possibility of doing it sufficiently quickly to re-

spond to the approach of the commonly used sub-sonic anti-tank guided missiles and unguided anti-tank rockets was indicated by the very short response times of the halon fire and explosion suppression systems which were successfully developed for tanks by the early 1980s.

However, the development of suitable countermeasures has continued to pose major problems. Small missiles or mortar-like bombs fired from launchers distributed around a tank are usually proposed but they can hardly be expected to score direct hits on the attacking missiles and the effectiveness of their blast or fragmentation warheads is in doubt. Other countermeasures, such as machine guns or high energy lasers, are possible. But the development of a countermeasure which would be effective and practicable appears to be the least tractable of the problems posed by active protection systems.

15.7 References

15.1 F C Thompson, *Report on Bullet Proof Steel for Tanks*, February, 1917, typescript in Library of Tank Museum, Bovington Camp.

15.2 J Dickie, 'Armour and Fighting Vehicles', Part 2, *Special Steel Review*, No.1, British Steel Corporation, 1969.

15.3 R C Laible, ed., *Ballistic Materials and Penetration Mechanics*, Elsevier, Amsterdam, 1980, pp.151-159.

15.4 J M Whittaker, *The Directional Probability Curve*, War Office (Science 1), London, December 1943.

15.5 *Elements of Armament Engineering*, Part 2, Ballistics, AMCP 706-107, US Army Materiel Command, Washington, 1963, pp.10-7 to 10-10.

15.6 *Automobile Bodies and Hulls*, AMCP 706-357, US Army Materiel Command, Washington, 1970, pp.2-24 to 2-26.

15.7 R M Ogorkiewicz, 'Using Aluminium Armour in Fighting Vehicles', *The Engineer*, Vol.227, No.5904, 21 March 1969, pp.450-452.

15.8 R Warren Piper, 'Aluminium – the Economic Armour Material', *Automotive Engineer*, Vol.1, No.5, June-July 1976, pp.48-49.

15.9 H P George, 'Light Armor Materials', *Weapons Technology*, American Ordnance Association, Washington, August 1961.

15.10 J J White and M J Wahl, *Shaped Charge Jet Interaction with Liquids*, 6th International Symposium on Ballistics, Orlando, 1981.

15.11 R P Hunnicutt, *Sherman*, Presidio Press, Novato, 1978, pp.224-225.

15.12 R P Hunnicutt, *Patton*, Presidio Press, Novato, 1984, p.123.

15.13 *Questionmark IV*, US Army Ordnance Tank-Automotive Command, August 1955, pp.3-8.

15.14 R P Hunnicutt, op.cit., p.124.

15.15 W Trinks, W Geiger and H Kollmannsperger, 'Grenzen der Schutzwirkung von Panzerwerkstoffen', *Jahrbuch der Wehrtechnik*, Vol.6, 1973, pp.46-50.

15.16 M Held, *Characterizing Shaped Charge Performance by Stand-Off Behavior*, 7th International Symposium on Ballistics, The Hague 1983, p.335.

15.17 R C Laible, op.cit., pp.136-139.

15.18 M Held, *A Structure for Protection Against Projectiles*, British Patent 1,581,125, 1974.

15.19 J S Nicholson, M C Rogers, R J Cox and G Merritt, *The Use of an Analytical Shaped Charge Jet and Target Response Model to Predict the Efficiency of Jet Disruption by Single and Multiple Explosive Armour Targets*, 9th International Symposium on Ballistics, Shrivenham, 1986, p.2-408.

15.20 M Mayseless, Y Erlich, Y Falcovitz and G Rosenberg, *Interaction of Shaped Charge Jets with Reactive Armour*, 8th International Symposium on Ballistics, Orlando, 1984.

15.21 D Yaziv, G Rosenberg and Y Partom, *Differential Ballistic Efficiency of Applique Armour*, 9th International Symposium on Ballistics, Shrivenham, 1986, pp.2-317 and 2-318.
15.22 *Questionmark IV*, op.cit., p.18.
15.23 R M Ogorkiewicz, 'Active Protection for Fighting Vehicles', *Jane's Defence Weekly*, Vol.3, No.16, 20 April 1985, pp.682-683.

Chapter 16

Configuration of Tanks

16.1 Evolution of the Conventional Configuration

Since tanks were originally built during the First World War, the great majority of them have had the same basic configuration. This has consisted of a hull with a driving compartment in the front part of it, an engine compartment in the rear and in between a fighting compartment surmounted by a rotating turret mounting the tank's armament.

Such a configuration was first put to use in the Renault FT light tank designed in France in 1916. However, the mounting of guns in rotating turrets was well established by then in naval construction and had been proposed in Britain for a wheeled armoured vehicle as early as 1899 (16.1). Moreover, an armoured car with a rotating turret was actually built in 1904 in Austria, by the Austro-Daimler Company, and many more turreted armoured cars were built in 1914 and 1915 (16.2). But, unlike the Renault FT, the armoured cars had their engines at the front.

The turret of the Renault FT was occupied by one man, as were those of several other light tanks which followed its general pattern during the 1920s and 1930s. They included the German Pz.Kpfw.I, which was produced from 1934 to 1937, all French light tanks up to the AMX-38 of 1940 and several Soviet light tanks, until the production of the T-70 was discontinued in 1943. One-man turrets then ceased to be used because they required the men occupying them to perform too many functions, namely those of commanding or controlling their tanks and firing their armament as well as loading it, which prevented tanks from being used as effectively as they could be. This became particularly evident as one-man turrets were armed not only with one or two machine guns but also with manually loaded cannons, which grew in calibre to 45 or 47mm, and as more came to be expected of tanks in terms of battlefield tactics.

In consequence, an increasing number of tanks was built during the 1930s with two-man turrets. This was true even of light tanks, such as the British Light Tank Mark IV of 1935, the main armament of which was only a 12.7mm heavy machine gun, and the German Pz.Kpfw.II which was produced from 1936 to 1942 and which was armed with a 20mm cannon. Other, more powerful tanks, which were armed at the time with guns of 37 to 47mm, were similarly provided in most cases with two-man turrets. These continued to be used in light tanks and armoured cars even when they were armed with guns of larger calibre, which by the 1960s rose to 90mm.

At first some heavier tanks were also built with two-man turrets. The prime

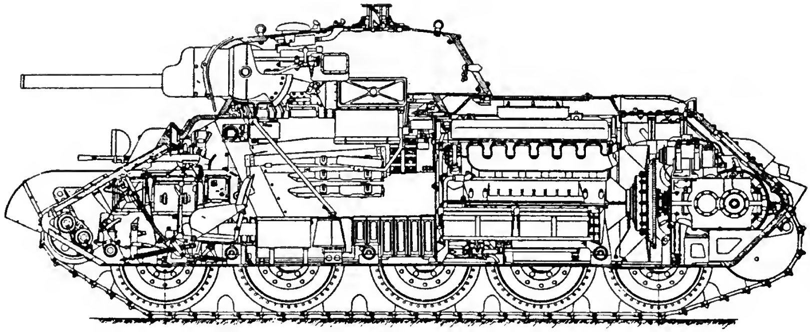


Fig. 16.1 Cross section of the Soviet T-34 medium tank.

example of this was the Soviet T-34, which was produced with a two-man turret mounting a 76mm gun until 1944. However, in two-man turrets with manually loaded guns one of the two men was still expected to perform more tasks than he could effectively carry out. This was generally the commander who not only had to command his tank but who also either had to fire the tank's weapons, as he did in the T-34, or to load them, as he has had to do in most light tanks and armoured cars. The principal effect of this has been that the commander of a tank with a two-man turret has not been able to give full attention to the tactical situation and to controlling his tank – and in the case of unit commanders' other tanks – so that they responded to it most effectively.

The conflict between their primary command function and those of a gunner or of a loader which has faced the commanders of tanks with two-man turrets has been somewhat less serious in the case light tanks intended mainly for reconnaissance. In that case tanks are not meant to engage in sustained combat and their weapons are expected to be fired relatively infrequently, so that their commanders only have to double as gunners or loaders from time to time and not for long. This has made two-man turrets with manually loaded guns acceptable for light reconnaissance tanks and for armoured cars, which have continued to be built with them to this day.

In contrast, most heavier tanks have had a commander free of the task of firing or loading their main armament. This started with the original turretless British tanks of the First World War and the need for a commander free to command began to be generally recognised in the case of turreted tanks during the 1930s. As a result an increasing number of medium as well as heavy tanks had turrets designed to accommodate a commander as well as a gunner and a loader.

The trend towards tanks with three-man turrets started with the British A.1 Independent heavy tank built in 1926 and, so far as British tanks are concerned, became firmly established in 1929 with the construction of the two A.7 medium tanks, whose three-man turrets served as a model for several British tanks designed during the 1930s (16.3). A little later three-man turrets were also adopted in Germany, first for the experimental *Neubaufahrzeug* built in 1934 and then for the Pz.Kpfw.III and IV. By the end of the Second World War in 1945 their use had spread to almost all medium and heavy tanks.

Until the end of the Second World War it was also generally considered that medium and heavy tanks should have not only three men in their turrets but also

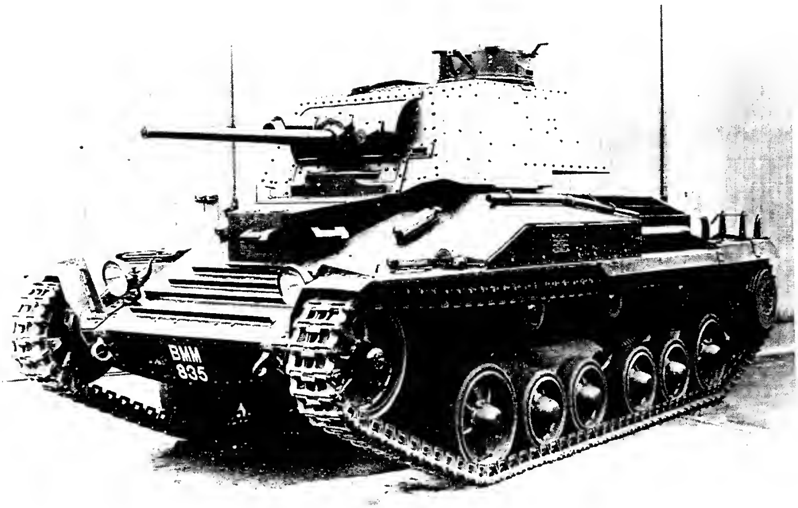


Fig. 16.2 British A.10 E.1 tank built in 1937 with what has become the conventional configuration of tanks. (Vickers-Armstrongs)

an additional crewman in the hull, alongside the driver. As a result, during the latter part of the war almost all medium and heavy tanks had crews of five men.

The fifth crewman served a machine gun mounted in the front of the hull and in a number of cases also operated the tank's radio, which otherwise came to be operated in the turret by the loader. His inclusion in the crew of tanks was very largely a consequence of the preoccupation in the early days of tank development with machine guns, which led to several tanks being built during the 1920s and 1930s with one, two or even four auxiliary, one-man machine gun turrets. The value of these turrets was very doubtful and they were very wisely abandoned during the Second World War, although the British Crusader and the Canadian Ram tanks were still being produced with an auxiliary machine gun turret in 1942.

If there had to be an additional, independently operated machine gun it was much more sensible to mount it in the front plate of the hull superstructure, which avoided the complication of the auxiliary turret and its detrimental effect on the ballistic shape of the hull front. In fact, this was done in the British A.7 medium tanks and it became standard practice by the end of the Second World War, when almost all tanks had a machine gun in the hull superstructure or glacis plate operated by a crewman sitting alongside the driver.

However, the inclusion of the fifth crewman was highly questionable. It was defended on the grounds that he not only operated an auxiliary machine gun but also increased the number of men available for maintaining a tank and for carrying out duties outside it. Nevertheless, he was dispensed with in the British A.10 E.1 cruiser tank prototype built by Vickers-Armstrongs in 1937 which, for the first time, had a three-man turret and only a driver in the hull. The example of the A.10 E.1 was followed in the design of the British A.13 cruiser tanks and of the Matilda

infantry tank, which were used during the early part of the Second World War. But the eminently sensible crew arrangement pioneered by it did not begin to be generally adopted until 1944, when the Soviet IS-1 heavy tank was introduced.

By then it had become obvious that the space occupied within tanks by the fifth crewman could not be justified by anything he did. This was particularly true in view of the increases which had taken place in the size of tank gun rounds and of the problem of stowing an adequate number of them in tanks. In consequence, the crew was confined to four men not only in the IS-1 but also in the British Centurion and the Soviet T-54, both of which were designed towards the end of the Second World War. From then on almost all battle tanks with manually loaded guns have had four-man crews consisting of a commander, a gunner, and a loader in the turret and a driver in the hull. The only exceptions to this are two US tanks built during the 1950s, which still had five-man crews. One of them was the M47 medium tank, which still had a hull machine gunner and therefore a five-man crew because its hull was based on that of an earlier, war-time tank. The other was the M103 heavy tank, which had two loaders in the turret because of the heavy weight of the ammunition of its 120mm gun.

16.2 Internal Volume and Dimensions

The elimination of the hull machine gunner from tanks designed since the Second World War reduced the amount of space required within them on his account by at least $1 m^3$. But this did not make tanks correspondingly smaller because the space previously occupied by the hull gunner was used up by the growing requirements of ammunition stowage.

The growth in the volume required by the ammunition was not due to an increase in the number of rounds carried in tanks, which was actually decreasing, but to the growth in the size of the individual rounds with the increase in the calibre of tank guns. Thus, on the eve of the Second World War the British A.9 and A.10 cruiser tanks carried 100 rounds for their 40mm guns and the Covenanter cruiser tank of 1940 carried 131 rounds while the original version of the German Pz.Kpfw.III carried as many as 150 rounds for its 37mm gun. In 1942 US M4 medium tanks still carried 97 rounds for their 75mm guns and the contemporary German Tiger I heavy tank carried 92 rounds in spite of being armed with a much more powerful 88mm gun. But the number of rounds carried by the Soviet T-34 tanks was reduced from 100 to 77 as they were armed in 1943 with more powerful 76mm guns and the T-34-85 could only carry 55 rounds for its 85mm gun while the IS-3 could carry no more than 28 rounds for its 122mm gun.

The increase in the amount of space required within tanks by the ammunition which took place during the Second World War is illustrated by the fact that the 100 rounds of 40mm ammunition of the British cruiser tanks took up only about $0.11 m^3$ of their internal volume while the 97 rounds of 75mm ammunition of the US M4 medium tanks occupied $0.37 m^3$ and the 92 88mm rounds of the Tiger I took up $0.81 m^3$.

For a time increases in the size of the rounds were accompanied by increases in the overall size of tanks and the total volume of the ammunition remained an almost constant proportion of their internal volume at around 5 per cent, although in absolute terms it increased. In consequence, the number of rounds did not have to decrease with the growth in the size of the ammunition. But by the end of the Second World War the size of tanks began to approach the limit of what was practicable and although the elimination of the fifth crewman provided some more

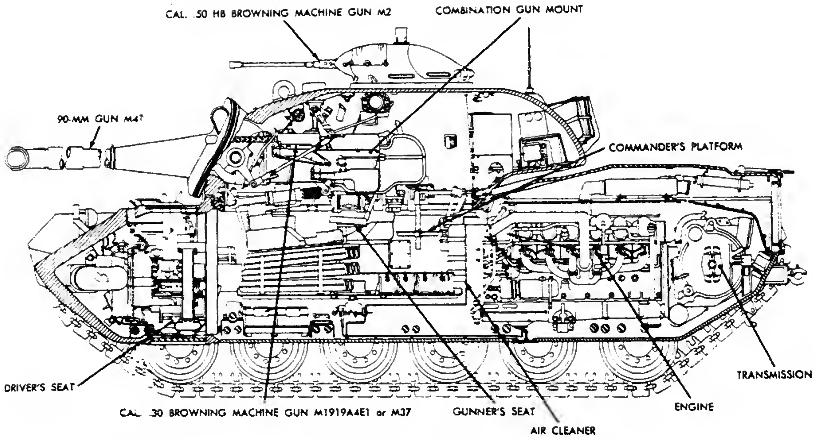


Fig. 16.3 Cross section of the US M48A2 medium tank. (US Army)

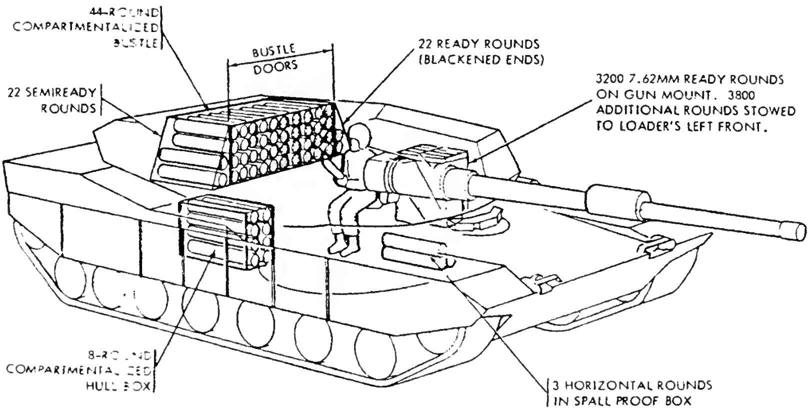


Fig. 16.4 Stowage of ammunition in the US M1 tank.

space for the ammunition further increase in the size of the rounds could only lead to reductions in their number.

The actual number of rounds carried by tanks produced during the 1950s with guns of more than 90mm ranged from 34 which the Soviet T-54 had for its 100mm gun to the 65 rounds which the British Centurion 5 had for its 105mm gun. The US M60A1 had only two 105mm rounds fewer but of the other tanks with 105mm guns introduced during the 1960s the French AMX-30 carried only 47 rounds. The contemporary German Leopard 1 had 60 rounds for its 105mm gun but Leopard 2, which is armed with a 120mm gun, has only 42 rounds for it. A similar reduction, from 55 to 40 rounds, occurred when the 105mm gun of the US M1 tank was replaced by a 120mm gun in its M1A1 version.

The number of rounds carried in the Israeli Merkava was also reduced from 62

to 50 rounds when the 105mm gun of the Mark 1 and 2 was replaced by the 120mm gun of the Mark 3. Other tanks built during the 1980s with 120mm guns carry about 40 rounds and this has become the norm. As before, some of the rounds are stowed in the turret, where they are within easy reach of the loader, and the rest is generally stowed in the hull by the side of the driver where it is given the maximum of protection by the heavy frontal armour.

From the loader's point of view the most convenient location for the ready rounds is in the turret bustle and in the US M1, as well as M1A1, almost all of the ammunition is stowed there. Ammunition stowed in the turret bustle can also be easily separated from the crew by sliding doors, as it is in the M1. Moreover, the roof of the bustle can be provided with blow-off panels to vent gases generated by rounds set on fire by a hit and thus prevent a catastrophic build up of pressure within the ammunition compartment (16.4). On the other hand, rounds are more likely to be hit when they are in the turret bustle than lower in the tank. For this reason none are stowed above the level of the turret ring in several tanks, including the British Challenger, the Israeli Merkava and the South Korean Type 88.

The total volume of 40 rounds of 120mm gun ammunition amounts to about $0.8m^3$ but the space they take up together with the stowage racks or bins and the associated free volume is equal to at least twice their own volume. Additional space is required for the inboard part of the gun and its recoil and elevation movement. At first this was relatively small but in tanks built since the 1950s the volume swept by the gun has amounted, typically, to about $1.3m^3$. However, a much greater amount of space is required by the crew of a tank. Thus, on average, a crewman requires at least $1.2m^3$ of space within a tank. In consequence, a conventional, four-man tank with an average amount of ammunition and a typical gun needs to have a minimum internal volume of $7.7m^3$, excluding its power pack. In fact, this is almost exactly the internal volume of the Soviet T-54 and T-55 tanks. But other tanks, with more generous internal dimensions, have had as much as $2m^3$ of space per crewman. In the case of a conventional four-man tank this implies an internal volume of $10.9m^3$, which happens to be that of the US M60A1, excluding, as before, the volume of the power pack.

The additional space required by the engine and the transmission is generally equal to between 30 and 40 per cent of the total internal volume. In the case of the Soviet T-55 the volume of the engine and transmission compartment is actually $4.3m^3$, so that its total internal volume amounts to $12m^3$. On the other hand, the engine and transmission compartment of the US M60A1 has a volume of $7.2m^3$ which, together with the fuel tanks, makes its total internal volume equal to $18.4m^3$. For all practical purposes these figures represent the extremes, as the internal volumes of almost all other tanks fall between those of the T-55 and the M60A1.

Apart from determining the minimum internal volume that tanks can have, their crews and guns also govern some of their principal dimensions. One of them is the turret ring diameter – the inside diameter of the turret bearing assembly – which is the principal parameter of turret size. In the case of one-man turrets mounting a single machine gun this can be only 710mm but about the smallest diameter that a two-man turret with a small calibre cannon could have was 1187mm of the US M3 light tanks. Three-man turrets with medium velocity 75 or 76mm guns needed a ring diameter of not less than about 1400mm. Turrets with a ring diameter of 1378mm were actually mounted on the British Churchill infantry tanks but the contemporary US M4 medium tanks, which were armed with similar guns, already had a diameter of 1753mm. This made it possible to rearm them later with

more powerful guns and the same 1753mm turret ring diameter was adopted for the M26 Pershing medium tank which was armed with a 90mm gun.

A further increase in turret ring diameter, to 1854mm, took place in the US M47 tank and a slightly larger diameter of 1880mm was adopted for the British Centurion. Similar increases took place in Soviet tanks. Thus, the 1440mm diameter of the T-34 was followed by the 1600mm diameter of the T-34-85 and then by the 1830mm diameter of the T-54 and T-55. A still larger diameter of 1980mm was adopted in the 1950s for the German Leopard 1 and has been retained for the Leopard 2 as well as the South Korean Type 88 and the Engesa Osorio. However, an even larger diameter of 2159mm was adopted for the US M48 and then the M60 and M1 tanks and also for the British Chieftain and Challenger. Turret ring diameters as large as this are close to the maximum possible within the limits on the overall width of tanks which have been described earlier and they can only be used if tank hulls have sponsons, so that the turret bearing can extend sideways over the tracks.

In addition to the progressive increases in the diameter of the turret ring, the growth in the size of tank guns and of their ammunition also caused a change in the disposition of the turret crew. At first the gunner was generally located on the left of the gun, which was logical when guns were controlled in elevation by means of a shoulder piece. In consequence, the loader was on the right of the gun. To give the loader the maximum amount of space for handling the rounds, the commander sat behind the gunner or, when the guns were still small enough to allow this, behind the gun which was the best place for him from the point of view of all-round vision.

Such an arrangement continued to be used in British and German tanks to the end of the Second World War and in Soviet tanks up to the T-62 tank of the 1960s. However, in the US M4 medium tank the gunner and the commander were located on the right and the loader on the left of the turret. This arrangement became standard in US tanks and after the Second World War in all other tanks, except for those of Soviet design. The reallocation of the left side of the turret to the loader became particularly appropriate so far as he was concerned as tank gun rounds grew progressively heavier and longer, until the overall length of the one-piece 120mm APFSDS rounds reached almost 1m. This made them difficult to handle but at least they were easier to load from the left than from the right of the gun.

The loaders have generally worked standing up and their height, together with the ground clearance, has therefore governed the minimum height of tanks. In consequence, the height to the turret roof of the lowest of the recently built conventional tanks has not been very different from the 2.14m height of the Renault FT of 1918. Thus, the height of the French AMX-30 is 2.28m and that of the South Korean Type 88 is 2.25m. On the other hand, the height to the turret roof of the US M60A3 is 2.71m, which is the maximum so far as recently built tanks are concerned.

Drivers have similarly governed the depth of tank hulls. Thus, for a driver in a normal sitting position the height of the hull from its floor to its roof has to be not less than about 1m. As long as turrets were relatively small there was little incentive to make hulls less deep, because the combined height of the hulls and turrets did not exceed that required by the loaders. But as turrets grew larger it became desirable to reduce the depth of hulls to keep down the overall height of tanks. As a result, a reclining or supine position began to be adopted for drivers, which made it possible to reduce the depth of hulls to a minimum of about 0.8m.

The first and for a time the only tank to be produced with a supine driving position was the British Chieftain but since the 1960s reclining, or semi-reclining, driving positions have been adopted in other tanks, including the US M1 (16.5). A prone position has also been considered for drivers but it has not proved satisfactory for a number of reasons. They include the stresses it imposed on the driver's neck and, if an attempt is made to reduce the latter by a chin support, skin irritation. Moreover, unlike the supine position, the prone position does not allow the driver to change easily from it to a conventional, head-out driving position.

16.3 Weight Distribution and Cost

The internal volume which tanks need to accommodate their crews, armament and power units determines not only their size but, to a large extent, also their weight. This is due to the fact that much of the weight comes from their armour envelope and the weight of the latter depends, in turn, on the space it has to enclose as well as the thickness of the armour.

The contribution of armour protection to the weight of tanks has varied from 35 per cent of the total in the case of light tanks such as the US M551, to 56.9 per cent in the case of the Soviet IS-3 heavy tank. However, in well protected battle tanks of recent years the percentage of the weight accounted for by armour has generally fallen within the narrower range of 45 to 51 per cent and its weight per unit of internal volume has been between 1.3 and 1.7 ton/m^3.

The weight of armour per unit of internal volume of relatively lightly protected battle tanks has been less than 1 ton/m^3 and that of some light tanks only 0.5 ton/m^3. However, even if the armour shell were reduced to the minimum governed by structural rather than ballistic consideration it would still account for about 20 per cent of the total weight of the vehicle.

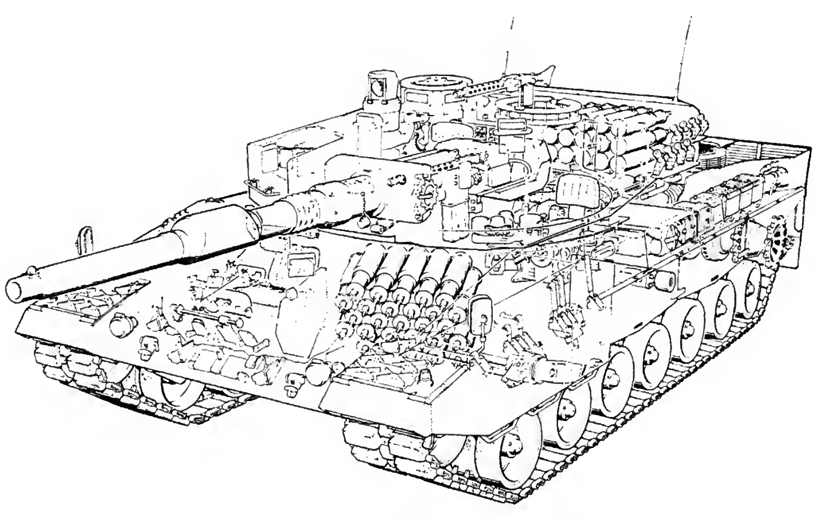


Fig. 16.5 Location of the ammunition and other components in the German Leopard 2 tank. (Krauss-Maffei copyright)

After armour the most important contribution to the weight of tanks is made by their running gear, that is by their suspension and tracks. This has been remarkably constant at 20 to 23 per cent, of which 11 to 13 per cent is generally accounted for by the suspension and 8 to 10 per cent by the tracks.

The third major contribution to the weight is due to the propulsion system, the principal components of which are the engine, the transmission and the final drives. As a percentage of the total this has also been almost constant, at about 12 per cent, in spite of all the developments in engines and transmissions which have taken place over the years.

Of the remaining components, guns and their mountings account for only about 3 to 7 per cent of the total weight of battle tanks, in spite of the progressive increase in their size. However, the trend towards arming light tanks with the largest possible guns has resulted in the percentage of the total weight due to them rising to 10 in some of the light tanks.

The increases in the size of the guns and the accompanying reductions in the number of rounds carried for them has resulted in their ammunition weighing significantly less than they do themselves. Thus, a typical load of 63 rounds of 105mm gun ammunition weighs about 1200kg while a 105mm M68 gun which fires it weighs 1891kg, together with its mounting. This compares with a typical load of 42 rounds of 120mm gun ammunition which weighs about 850kg and the widely used Rh 120 gun which fires it and weighs 3015kg with its mounting.

The weight of the fuel which tanks carry is of the same order as that of the ammunition. The capacity of their fuel cells ranges generally from about 900 to 1400 litres or, in the case of the gas turbine powered US M1 tank, to a maximum of 1907 litres. In consequence, the weight ranges from about 750 to 1160kg of diesel fuel or, in the extreme, to 1530kg of gas turbine fuel.

In addition to the ammunition and the fuel, there are various miscellaneous items of stowage and, of course, there is also the crew, which when fully equipped weighs on average 95kg per man. Their combined weight is such that when tanks are combat loaded they generally weigh 2 tons more than they do when they are empty.

Apart from its various physical effects, the weight of tanks has also been taken as a measure of their financial cost. There was considerable justification for this when the cost of tanks was due largely to their armour and mechanical components and when it could be assumed, therefore, that their total cost was roughly proportional to their weight. However, this ceased to be tenable as more and more of the cost of tanks was due to the sighting and electronic equipment with which they were being fitted and which contributed little to their weight. A good illustration of the progressive increases in the relative cost of the electronic and associated equipment is provided by French tanks in which it rose from being equal to only 10 per cent of the total cost of the AMX-30B to 15 in AMX-30 B2 and 30 in AMX-40 and then to as much as 50 per cent in the AMX Leclerc (16.6).

The change in the cost structure of tanks was first highlighted during the late 1960s by the US-German MBT-70, whose fire and gun control equipment accounted for 43 per cent of its cost. This was considered unacceptably high and was largely responsible for the MBT-70 and its US follow-on, the XM803, being abandoned. Nevertheless, the relative cost of the fire and gun control equipment of tanks which followed the MBT-70 was considerably higher than that of the earlier tanks. For example, it accounted for 23 per cent of the cost of the US M1.

An important concomitant of the increases in the cost of the fire and gun control

equipment has been a decline in the relative cost of the automotive components of tanks and of the whole chassis, which originally dominated their overall cost.

16.4 Rear versus Front Engine Installations

Although most tanks have had their engines at the rear of the hull, in a considerable number of them the engine has been at the front. A front engine location was adopted as early as 1917 for the British Medium A but one of its principal advantages did not begin to emerge until the 1920s, when the Vickers Medium was produced with an engine not only located at the front of the hull but also with the driver alongside it. Such an arrangement made possible a more compact and in particular shorter hull. This was exploited in the design of several light tanks, from the British Mark V and VI of the 1930s through the French AMX-13 introduced in the 1950s to the British Scorpion developed during the 1960s.

A similar arrangement with the engine and driver located alongside each other at the front of the hull was also adopted during the 1970s for the Israeli Merkava battle tank. But in this case it was adopted not because it minimised the length of the hull but because it interposed the engine between the crew and the most likely direction of attack, which is of course from the front, and thereby made the engine contribute to the protection of the crew.

The first deliberate use of an engine to increase the protection of the crew against attack from the front has been in the Swedish S-tank developed during the 1960s. However, in its case the engine compartment is located right across the front of the hull. This has also contributed to it being compact but the underlying reason for it is its unconventional, turretless configuration. The location of the engine compartment at the front of the hull has also given the S-tank the advantage of having its ammunition at the rear of the hull, where it is least likely to be hit and where it can be loaded much more easily, through hatches in the rear hull plate, than in conventional, rear-engined tanks.

In the Merkava the advantages offered by an ammunition compartment located at the rear of the hull have been exploited further by leaving a passage between the stacks of ammunition containers and introducing a personnel hatch in the rear of the hull. At the expense of some increase in the internal volume, this has provided the crew with an alternative to the traditional mode of entering or leaving tanks through hatches in the top of the turret or of the hull, which is much safer when a tank is under fire. Moreover, the ammunition containers in the Merkava are removable so that its rear compartment can be used to carry a command team, or four wounded on stretchers or up to ten infantrymen instead of the ammunition.

In addition, the location of its engine at the front of the hull results in the turret of the Merkava being more towards the rear than those of conventional tanks, which reduces the protrusion of its gun over the front of the hull and consequently the risk of damage to the gun during the crossing of ditches and similar obstacles.

On the other hand, access to engines is generally more difficult when they are located at the front instead of the rear of hulls, because they are then under the heavy frontal armour. In the case of the Merkava access for routine maintenance can be gained by swinging open, by hand, a small, hinged part of the glacis. Otherwise the whole glacis has to be lifted off, which can only be done using a crane. However, this would have to be done only if the power pack were to be removed in which case a crane would be needed anyway.

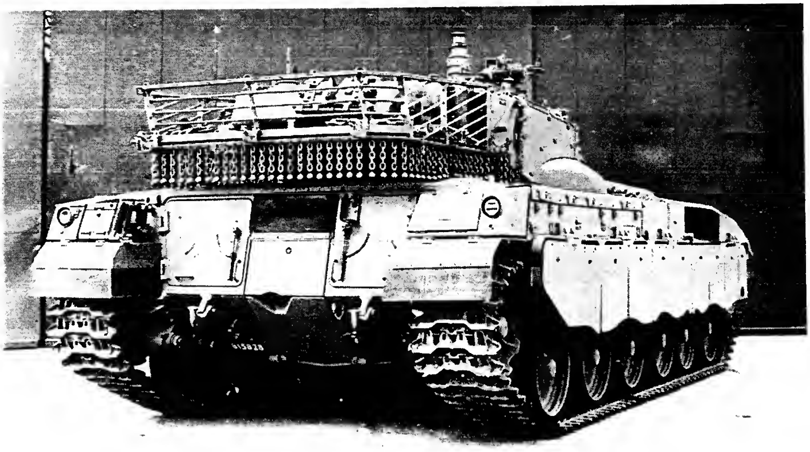


Fig. 16.6 Rear hatch of the front-engined Israeli Merkava tank. (IDF)

The location of the engine at the front of the hull also makes it more difficult to provide inlets and outlets for the engine cooling air without creating weak spots, or ballistic windows, in the frontal armour. It also increases the height of the front of the hull and consequently the weight of armour for a given level of protection.

At first the choice between locating engines at the front or the rear was unrelated to the choice between the track driving sprockets being at the front or the rear. Thus, in addition to those which had both the engine and the sprockets at the front or at the rear, there were tanks such as the Vickers Medium with the engine at the front and the sprockets at the rear. There were also many others, including the US M4 medium tanks and German tanks from the Pz.Kpfw.I to Tiger II which had the engine at the rear and the sprockets at the front. However, the location of the engine and of the sprockets at the opposite ends of a tank made necessary a transmission shaft running from one end to the other, which took up space within the hull and increased the height of the tank. The disadvantages of this were recognised at an early stage (16.7). In fact, the combination of an engine at the rear and sprockets at the front was very wisely eschewed almost completely in Britain, where only a few light tanks were built with it. But it was only after the Second World War that this arrangement was generally abandoned. Since then only one more tank has been built with it, the Type 61 produced in Japan during the 1960s.

Otherwise all tanks built since 1945 have had their sprockets as well as the transmissions at the same end of the hull as the engine. When they are at the front sprockets enjoy the advantage of stones and mud falling out of the tracks before they engage with them, which reduces wear and the risk of damage or of tracks being forced off the sprockets by mud packing between them. On the other hand, with a front sprocket the slackest section of the track is between it and the first road wheel and this can cause the latter to run off the track. Track shedding can therefore be promoted by the use of front as well as rear sprockets, albeit for a different reason.

With a front sprocket more of the track and in particular its top run is under full

drive tension, which acts on it as it passes round the idler wheel. This increases friction losses due to the flexing of the track and consequently rolling resistance, which is generally greater with front than with rear sprocket drive.

16.5 Oscillating or Trunnion-Mounted Turrets

Several departures from the conventional configuration of tanks have involved the use of turrets of a different kind from that normally used. One of them has been the oscillating or trunnion-mounted type of turret. The basic feature of this type of turret is that instead of being in one piece it consists of two parts – one above the other. The upper part is mounted on trunnions in the lower part and has the gun fixed in it, so that they move together in elevation, while the lower part rotates in azimuth on a turret bearing in the usual way.

Oscillating turrets were pioneered in France and were introduced almost simultaneously on the prototypes of the Panhard EBR eight wheeled armoured car, the AMX-13 light tank and the AMX-50 battle tank, which were built in 1948 and 1949. The turret of the EBR differed from those of the two tanks in not having a bustle, so that the rear of the upper part moved down into the lower part when the gun was elevated, which made it considerably lower than the others. But its gun was still loaded manually while the others, with the bustle, could carry in it an automatic or semi-automatic loading mechanism permanently aligned with the gun and therefore relatively simple. Full advantage of this was taken in the AMX-13, the bustle of which was fitted with a semi-automatic loading system with two drums each holding six rounds. Either drum could be rotated by the gunner, through a hand-driven quill shaft and gears, to tip a round on to a loading tray. The gunner could then trip a recoil-cocked, spring loaded rammer to load the gun. As a result, the AMX-13 could be armed with a 75mm gun as powerful as that mounted previously in the much heavier Panther tank and yet have a turret with a crew of only two men.

Like the others, the oscillating turret of the AMX-13 also offered the advantage of a simple and virtually foolproof system of sights for the gunner and the commander, which were fixed in its upper part. They did not, therefore, move in relation to the gun, so that once they were bedded in they seldom required further boresighting. The oscillating turret also made it possible to mount the gun much closer to the turret roof than in any conventional turret, because no space had to be

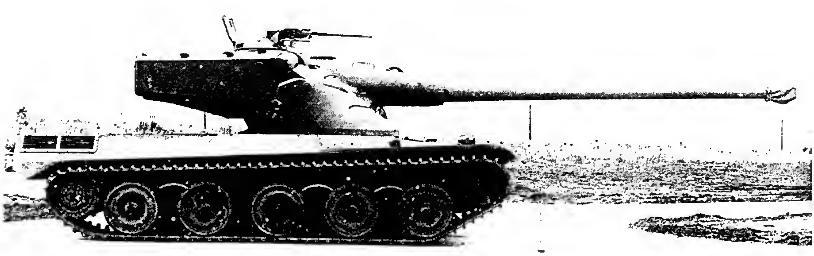


Fig. 16.7 French AMX-50 with an oscillating turret mounting a 120mm gun. (French Army)

provided under the roof for the upward movement of the breech end of the gun. This minimised the height of the turret which had to be exposed by the AMX-13 to fire from behind cover and, therefore, reduced the chances of it being hit in defensive positions.

However, the stowage of the ammunition in the turret bustle increased the risk of it being hit by enemy fire and the two ammunition drums in the bustle could only be reloaded from outside, through hatches in the turret roof. The overhanging bustle also restricted the elevation that the oscillating turret could provide to the gun mounted in it to 12.5°. What is more, the joint between the two parts of the oscillating turret was difficult to seal against radioactive dust and airborne chemical agents, or against the entry of water if the tank was used for the deep fording of rivers. In addition, the relative movement between the two parts of the oscillating turret required their armour to overlap to a significant extent and this made it heavier than a corresponding conventional turret.

The handicap of heavier weight was not serious in the case of a relatively lightly armoured FL 10 turret of the AMX-13 or the FL 11 turret of the EBR and they were both produced and used in considerable numbers. What is more, the 75mm gun FL 10 turret was developed in the mid-1950s into the FL 12 turret armed with a medium velocity 105mm gun which was mounted not only on a later version of the AMX-13 but also, in a modified form, on the SK 105 Kürassier tank destroyer produced in Austria during the 1970s and 1980s by Steyr-Daimler-Puch.

However, the disadvantages of the oscillating turrets outweighed their advantages when it came to their use on battle tanks, which did not advance beyond the AMX-50 prototypes and which was abandoned in France in the mid-1950s in favour of a return to conventional turrets (16.8).

A similar fate befell the development of oscillating turrets for battle tanks in the United States, which started in 1951. It was inspired by the example of the French vehicles and in particular of the AMX-13, the second prototype of which was tested in the United States in 1950. Its first practical outcome was the construction in 1955 of the T69 tank which consisted of an oscillating turret with a 90mm gun and an automatic loading system mounted on the chassis of a T42 medium tank prototype (16.9). In spite of its automatic loading system, the turret of the T-69 tank still had a crew of three, a human loader being retained to replenish an eight-round drum magazine which was located not in the bustle but under the gun. Because the magazine was not located in the bustle, the automatic loading system of the T69 was more complex than that of the AMX-13. But it did provide a high cyclic rate of fire, of up to 33 rounds per minute, which was the principal objective of the contemporary development of automatic loading systems in the United States.

However, development of the T69 was abandoned after tests carried out in 1956. By then another oscillating turret was developed for the T54E1 tank as an alternative to the conventional turret of the T54 version. Like the T54, the T54E1 was armed with a 105mm gun and used the chassis of the M48 medium tank. Its turret resembled that of the T69 in having a crew of three and an automatic loading system with a drum magazine, with nine rounds, under the gun. But the development of the T54E1 was not even taken as far as that of the T69 before it was discontinued in 1956. Much the same thing happened to the T77 tank, which consisted of an oscillating turret with a 120mm gun on a M48 medium tank chassis, to the T57 tank, which consisted of a similar turret on a T43 heavy tank chassis, and to the T58, which consisted of an oscillating turret with a 155mm gun mounted on a T43 chassis (16.10). As before, the turrets of these tanks had

three-man crews and contained automatic loading systems with a drum magazine under the gun, except for the T58, which had the magazine in the bustle. Their development followed decisions taken in 1951, and like that of the other US tanks with oscillating turrets, was terminated at the beginning of 1957.

16.6 Low Frontal Area Turrets

Although the development of oscillating turrets in the United States came to an end in 1957, one feature which was devised during its course was carried over and embodied later in the design of another type of turret. This amounted to a lowering of the positions of the gunner and of the loader and a corresponding decrease in the height of the turret on either side of the gun, which reduced considerably its frontal aspect. In consequence it reduced the chance of the turret being hit from the front and, even more, of the tank being hit when in hull-down positions on reverse slopes or behind cover.

The first to incorporate this feature was an oscillating turret designed between 1952 and 1953 by the Rheem Manufacturing Company as part of a feasibility study carried out for the US Army Ordnance (16.11). The turret was to be armed with a 105 or 120mm gun and in it the gunner and the loader were to be seated so that their heads were below the level of the gun while the commander sat in the turret bustle immediately behind the gun, which reduced the frontal area of the upper part of the turret to little more than that of the armour around the gun.

No such turret was actually built but the concept of a low frontal area turret reappeared a few years later in the design of more conventional, one-piece turrets. The first of them was designed around 1960 for the MBT(MR), the tank which the US Army was proposing to develop at the time, and although this particular turret was not built a similar one was adopted in 1964 and subsequently produced for the M60A2 tank (16.12).

The advantage of a low frontal area was nullified in the M60A2 by fitting its turret with a ridiculously large commander's cupola. The M60A2 also suffered from the difficulty associated with manually loading guns in low frontal area turrets, although this was mitigated to some extent by the relatively short inboard length of its 152mm gun-launcher. The gun-launcher also allowed the commander to sit right behind it, so that he could look over the raised part of the turret all round, which is otherwise impossible for him to do in low frontal area turrets except through a panoramic periscope.

For all its shortcomings, the M60A2 demonstrated the potential advantages of low frontal area turrets and it is surprising that its example was not followed by other tanks. It did lead to low frontal area turrets being incorporated in some of the designs which were proposed in Germany in the early 1970s for KPz 3, the battle tank then being planned for the 1980s, but none of them was adopted (16.13).

It was only with the development of the Israeli Merkava that another serious effort was made to produce a tank with a low frontal area turret. The reduction of the frontal area of the Merkava has been less extreme than that of the M60A2, if one ignores the latter's cupola, mainly because the commander is located relatively high behind the gunner, so that he can look all round over the turret roof, and because the loader works standing up. On the other hand the height of the turret has been reduced by moving the gun trunnions closer to the breech, to reduce the room required behind and above the latter at full depression, while still allowing the depression to be 8°. As a result, the frontal area which the Merkava needs to expose when firing from behind cover is only 1.05m^2, compared with about 1.7m^2

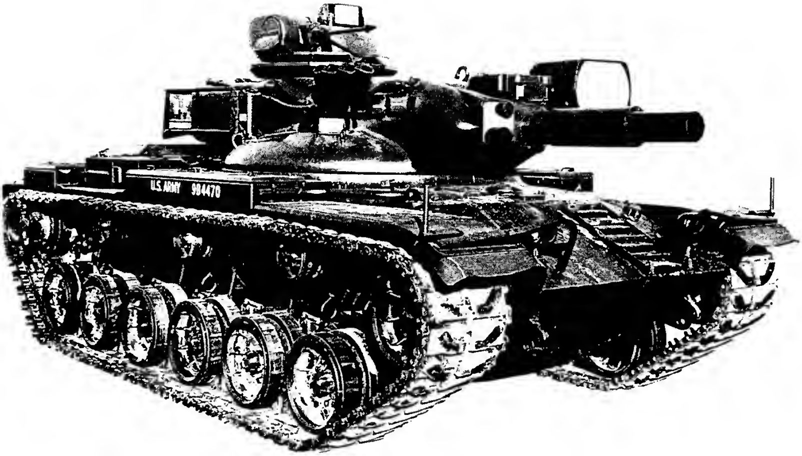


Fig. 16.8 US M60A2 tank with a low frontal area turret. (US Army)

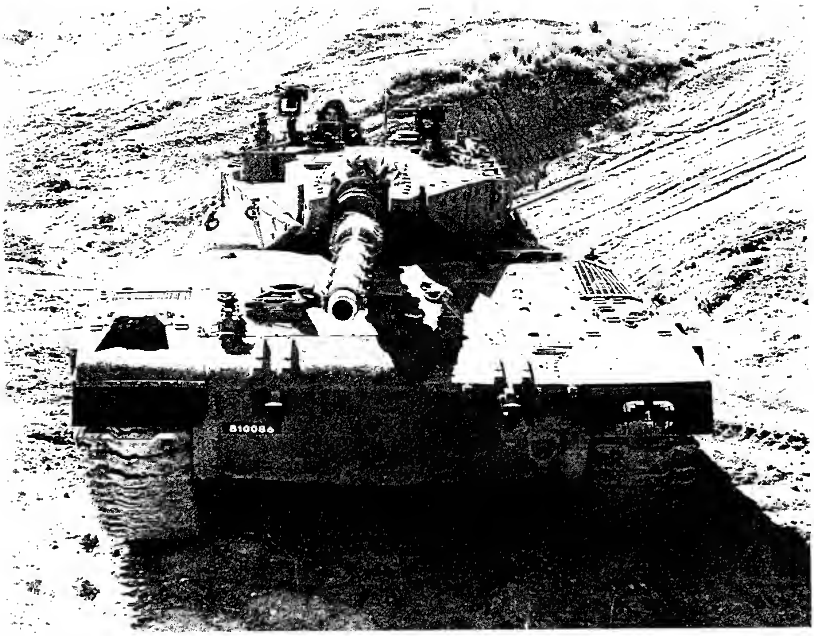


Fig. 16.9 Israeli Merkava Mark 2 with a low frontal area turret.

for the US M60A1, for instance. Its chances of being hit are therefore correspondingly lower, because the probability of a target being hit is roughly proportional to its area.

The only other significant reduction in the frontal area of turrets has been achieved in Soviet tanks, from the T-54 onwards. But this has involved reductions in the depression of their guns to only 4°, compared with 8° to 10° of other tanks. This has forced Soviet tanks to expose themselves to a considerably greater extent whenever they try to fire on approaching the crests of hills or even of small undulations of the ground that would otherwise provide them with a valuable degree of cover.

On the other hand, the development of spaced, multi-layered armour has increased considerably the frontal area of tanks. Thus, the total frontal area of the turrets of tanks such as the US M1 has risen to as much as $3m^2$, compared with about $2m^2$ of the earlier tanks with homogeneous steel armour.

The frontal area of the rest of the contemporary battle tanks, that is of their hulls and tracks, varies from about 4 to $5m^2$. This results in their total frontal area ranging from $5.6m^2$ of the Soviet T-55 to $7.7m^2$ of the US M60A1.

As before, the total area gives an indication of the probability of tanks being hit, but only when fully exposed. In general this is not the case because the irregularities of the ground over which tanks operate cover, on average, the first 0.7m of their height. In consequence, what matters is not so much the total frontal area but the area above the 0.7m, or so, from the ground. This makes the vulnerability of tanks more sensitive to their height than would otherwise be the case.

16.7 Externally Mounted Guns

Provided the crew and all the equipment can be accommodated in the hull, the frontal area of a tank can be reduced further by dispensing with a conventional or a low frontal area type of turret and mounting the gun externally, on a pedestal. The latter can stand on top of a manned 'pancake' turret, the top of which is almost flush with the roof of the hull, or directly on the hull, in which case the gun has to be traversed by remote control.

Both types of pedestal mountings require the gun to be loaded automatically and several different ways of doing this have been devised. The simplest involves locating a number of rounds in a magazine fixed to the gun mounting. The advantage of this solution is that there is no relative motion between the magazine and the gun, so that loading the latter is no more complicated than in an oscillating turret with a bustle magazine.

This method of loading an externally mounted gun was proposed as early as 1952 in a feasibility study sponsored by the US Army Ordnance, which involved the combination of a 105mm gun with 24 rounds in a self-contained armoured pod mounted on top of a manned turret (16.14). A somewhat similar solution was adopted for the first vehicle to be built with an externally mounted gun, the COMRES 75 test bed based on a Comet tank chassis which was built in 1968 in Britain at the Fighting Vehicles Research and Development Establishment. But in COMRES 75 the rounds were not on a conveyor chain around the gun as in the original US design but in two long tubular magazines on either side of its 83.8mm gun.

The advantages of relative simplicity which pedestal mountings of this kind offered were offset by the vulnerability of the ammunition located by the gun and none was adopted. However, COMRES 75 formed the basis of one of the designs

Fig. 16.10 British COMRES 75 test vehicle with an externally mounted 83.8mm gun. (MVEE, Crown Copyright Reserved)

considered under the abortive Anglo-German future main battle tank programme of the mid-1970s. Moreover, it was followed during the 1970s by at least two German designs of guns mounted on pedestals together with an ammunition magazine. One of them involved a flat magazine with two rows of rounds behind the gun and it was actually incorporated in a full-size mock-up of a tank. The other design featured a ring magazine with ten rounds around a 120mm gun (16.15).

Subsequent designs of pedestal mountings dispensed with the ammunition magazine at the gun and were, therefore, less vulnerable. One of them was developed at Bofors in Sweden in the mid-1970s. It involved the use of an arm which rotated about a one-man turret carrying the gun pedestal and which swung up to load the gun, in any position, with a round picked up by it from an ammunition magazine fixed to the rear of the hull.

The swinging and rotating arm loading system was also considered in Sweden for a gun mounted on a remotely controlled pedestal, which was to be used on the UDES XX 20 articulated tank destroyer of the early 1980s. In this case the axis of the pedestal coincided with the pivot between the two halves of the vehicle. However, the development of this type of mounting did not advance beyond a test rig, although it offered the advantage of a complete separation of the ammunition from the crew and of the ammunition magazine from the rest of the vehicle. On the other hand, it involved taking rounds, one by one, out of the vehicle and then loading them from outside into the gun. In consequence, it exposed the rounds to damage or to contamination by dirt during their transit from the magazine into the gun.

The disadvantages of an exposed path for the ammunition have been avoided by passing rounds to the gun through the pedestal on which it is mounted. To do this rounds have to be located in, or at least passed through, the turret so if the latter is manned ammunition can no longer be separated from the crew. Otherwise, feeding the ammunition through the pedestal represents an attractive solution, although the external mounting which goes with it leaves the gun less well protected than in a conventional turret.

The first major step towards the development of an external gun mounting with

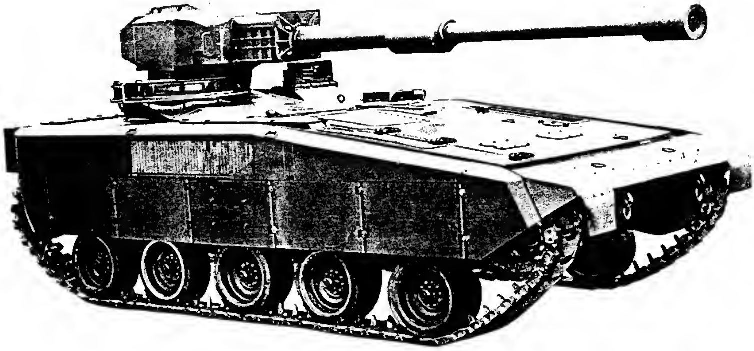


Fig. 16.11 Teledyne Armoured Gun System with an externally mounted 105mm gun. (Teledyne Continental Motors)

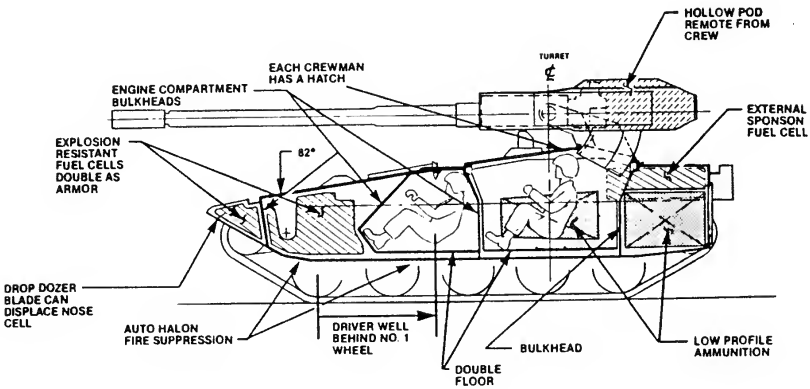


Fig. 16.12 Cross section of the Teledyne Armoured Gun System. (Teledyne Continental Motors)

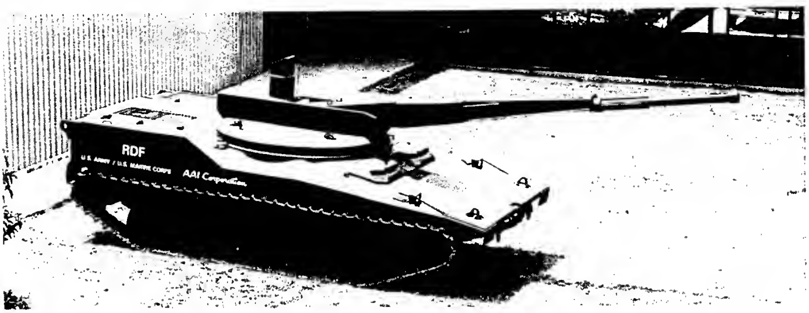


Fig. 16.13 Rapid Deployment Force Light Tank with an unmanned, remotely controlled turret with a 75mm gun. (AAI Corp.)

an ammunition feed through it was taken with the design in 1976 in the United States, of the HIMAG test bed vehicle by the National Water Lift Company. However, a battleworthy pedestal mounting with an ammunition feed through it did not appear until 1985 when Teledyne Continental Motors built the prototype of what was then called the Armored Gun System, or AGS.

The Teledyne AGS is a front-engined vehicle with a two-man pancake turret with a pedestal mounted 105mm gun. The gun is fed automatically from a nine-round horizontal drum magazine located between the seats of the two turret crewmen. Each of the nine rounds is contained in a cylindrical sleeve which is hinged at its front end and swings up when in its topmost position to offer its round to a carriage. This carries the round through the pedestal into the back of the gun pod and then forward into the breech of the gun. The magazine can be reloaded manually at any time or automatically, from two other drum magazines in the rear of the hull, when the turret is traversed so that the gun points straight ahead. Each of the two rear drums contains 10 ready rounds in an outer ring and five additional rounds in an inner ring and they can be easily reloaded from outside through access doors in the rear hull plate.

To achieve the remaining objective of separating the ammunition and the crew without resorting to a magazine at an externally mounted gun or to a swinging and rotating arm external loader, all the crewmen have to be seated outside the turret and the turret has to be operated by remote control. This inevitably complicates fire control equipment as the gunner no longer rotates with the gun, and it also eliminates to all intents and purposes any possibility of a reversionary, manual operation of the gun and turret. On the other hand, location of all the crewmen outside the turret means that they can be together, in visual and physical contact, which is highly desirable psychologically and makes it easier to share various tasks between them.

The development of vehicles with the crew separated from the weapon system and the latter operated, perforce, by remote control started in the United States with a design put forward in 1976 by AAI Corporation for the HIMAG test bed vehicle. It envisaged a very low silhouette vehicle with a crew of two located in the front of the hull and a small, remotely controlled turret mounting an automatically loaded 75mm gun. The design was not accepted but in 1977 AAI received a contract to built a vehicle which resembled it in some respects and which became known as the High Survivability Test Vehicle, Lightweight, or HSTV(L). But this vehicle still had one man in the turret. It was only after the HSTV(L) was built to US Army and US Marine Corps requirements that in 1980 AAI built, on their own initiative, the Rapid Deployment Force Light Tank (RDF/LT). This was very similar to the HSTV(L) but had a crew of only two men seated in the front of the hull and an unmanned, remotely controlled turret with a 75mm gun, as envisaged in AAI's original design.

Development of AAI's RDF/LT was confined to the construction of a prototype but in 1982 the US Army Tank Automotive Command decided to build a much larger vehicle with an unmanned, remotely controlled turret. This experimental vehicle, called the Tank Test Bed, was built by the Land Systems Division of General Dynamics and consisted of a modified M1 tank chassis and an unmanned, remotely controlled turret mounting a 120mm gun with an automatic loading system. Its three crewmen were seated alongside each other at the front of the hull and all the ammunition for its 120mm gun, which amounted to 40 rounds, was stowed vertically, nose down, in two almost complete concentric rings below the turret ring. This meant that the ammunition was not only separated completely

Fig. 16.14 Tank Test Bed with an unmanned, remotely controlled turret with a 120mm gun built by General Dynamics Land Systems Division on an M1 tank chassis. (General Dynamics Land Systems)

from the crew but, being within the height of the hull, was far less vulnerable than the ammunition stowed in the turret bustle of the M1 tank.

The turret of the Tank Test Bed was of the low frontal area type and this reduced considerably the size of the target which it represented by comparison with the M1 tank. Moreover, its critical target area, that is the frontal area within which the crew and the ammunition are located, was even smaller in relation to that of the M1. In fact, it was about 2.8m^2, compared with 3.8m^2, because the crew and all the ammunition were in the hull and this also meant that they could be protected by considerably heavier armour without exceeding the weight of the M1. However, the fire and gun control systems of the Tank Test Bed were inevitably complex and its design effectively ruled out any possibility of manual operation of the weapon system in the event of a component failure or damage.

16.8 Tanks with Driver in the Turret

The development of tanks with low frontal area turrets and with guns mounted on pedestals was preceded by what was, in effect, an alternative approach to reducing the size of the target which tanks offered. Thus, while the other developments attempted to do this by concentrating the crew and the ammunition in the hull, it concentrated them instead in the turret. The basic feature of this approach was the location of the driver in the turret. This avoided the two-tier arrangement of the crew in conventional tanks and, consequently, allowed a significant reduction in the overall height while retaining their general appearance. It also offered other advantages, which were dominant in some cases.

The first design of a tank with the driver in the turret appears to have been put

forward as early as 1946, by the Chrysler Corporation (16.16). Several more designs of tanks with the driver in the turret were proposed in the United States in the mid-1950s (16.17). Like the original Chrysler design, they incorporated a driver's station which rotated in the opposite direction to the turret, so that it always faced forward, and the principal object of them appears to have been to lower the silhouette of tanks.

A tank with a counter-rotating driver's station in the turret was also proposed in Britain around 1950, the object in this case of placing the driver in the turret being to optimise the ratio of surface, and therefore of armour, to the volume of the tank (16.18). Compactness was also the reason for the adoption of a limited traverse turret containing the driver in a design put forward in 1960 in Britain for the Armoured Vehicle, Reconnaissance (16.19).

None of these designs led to the construction of a vehicle but in 1956 a two-man light tank with the driver in the turret was built in France. However, this particular vehicle, the AMX ELC, could only be driven when its turret was pointing straight ahead (16.20). In other words, its turret could be traversed and its 90mm gun fired off its longitudinal axis only when it was stationary. This was acceptable for a vehicle which was to be used defensively but not if it was to move rapidly from one firing position to another. In any case, the AMX ELC was not adopted by the French Army, even though a second version of it was built and tested in 1961.

On the other hand, the US Army adopted three different self-propelled guns with the driver in the turret and they were put into service in the 1950s. They were the 105mm M52, the 155mm M53 and the 203mm M55. However, the traverse of their turrets was limited to a total of 120° in the case of the M52 and 60° in the case of the M53 and M55. Moreover, they were not expected to fire on the move nor to change firing positions as rapidly as tanks.

It was only during the mid-1960s that a tank was built which had the driver in the turret and was capable of operating like other tanks. This was the US-German MBT-70 which had the driver located in the turret in a counter-rotating 'capsule'

Fig. 16.15 MBT-70 with the driver emerging out of his station in the turret. (US Army)

to the left of its 152mm gun launcher while the other two crew members, the commander and the gunner, were on the right of the turret. The location of the driver in the turret helped to restrict the height of the MBT-70 to 2.29m, measured to the top of the turret roof, but the principal reason for its adoption was to concentrate all three crewmen in one compartment which would be provided more easily with nuclear, biological and chemical (NBC) protection.

The driver's station was geared to rotate about its axis in the opposite sense to the turret, so that the driver always faced in the direction of motion of the tank. However, it was not at the centre of the turret and therefore rotated also about the vertical axis of the latter, which subjected drivers to somewhat disconcerting effects. The installation of a counter-rotating driver's station in the turret also complicated driving controls. But, whatever problems were associated with their driver's station, the MBT-70 and its more austere US version, the XM803, did not advance beyond prototypes for other reasons.

After the XM803 was abandoned in the United States in 1971, the idea of locating the driver in the turret was kept alive in Germany where it was incorporated in the mid-1970s in one of the designs put forward during the course of the Anglo-German future main battle tank programme of the period. The proposed tank was to have a turret with a traverse limited to a total of 180° but even then the driver's station was considered to pose serious problems and its development was not pursued further at that stage. But during the 1980s new designs were put forward in Britain and in Germany for tanks with the driver in the turret. This time they were for two-man battle tanks which were to be as compact as possible without losing the advantages of having a rotating turret.

16.9 Conventional Turrets with Automatic Loading Systems

Although MBT-70 was not accepted itself, some of the design features introduced in it were subsequently adopted in other tanks. One of them was the automatic loading system, which was designed by Rheinmetall. It was located in the turret bustle and consisted of a magazine with 26 rounds, an extendable loading tube and a rammer (16.21). The rounds were held, pointing forward, in tubular containers that formed two rows and were connected by an endless chain which drove them round as required into alignment with the loading tube and rammer. To load it, the gun was decoupled from its elevation drive and brought into the horizontal position to align it with the loading tube, after which it was returned automatically to its original elevation.

This represented the simplest type of automatic loading system that could be installed in a conventional turret. In fact, it was as simple as the systems that can be installed in the bustles of oscillating turrets, except for the need to decouple the gun from the elevation drive and to index it for loading. It eliminated, of course, the need for a human loader and made it possible to separate the ammunition magazine from the crew by a bulkhead with sliding doors or a port with a hinged cover. At the same time it provided opportunities for a high degree of manual operation in emergencies. Almost the only disadvantage of it was that invariably associated with the stowage of ammunition high up above the turret ring. But this did not prevent similar automatic loading systems being adopted in the 1980s for the French AMX Leclerc and the Japanese TK-X battle tanks.

Another automatic loading system located in the turret bustle was developed in Germany during the 1980s for a proposed successor to the Leopard 2 tank which was to have a low-silhouette, two-man turret. But in this case the rounds were not

Fig. 16.16 Japanese TK-X battle tank prototype with an autoloader in the turret bustle.

arranged in line with the gun but at right angles to it, in double rows with the warheads facing outwards (16.22). This was supposed to reduce the danger to the crew created by ammunition fires and it also increased the number of rounds that could be carried in the bustle to about 40, compared with 22 in the AMX Leclerc. However, it also complicated the loading of the gun, took up more space and increased the rotational inertia of the turret.

The alternative type of automatic loading system installed in conventional turrets has consisted, in essence, of a magazine within the turret basket and of a hoist for lifting rounds up to the gun. Systems of this kind avoid the undesirable location of the ammunition in the turret bustle but while they reduce considerably the chances of the ammunition being hit by direct fire they make it more vulnerable to mines. Ammunition magazines within the turret basket also encroach on the height of the crew compartments, or add to it, and make it impossible to separate the ammunition from the crew, who in many cases have to sit on top of the ammunition.

Nevertheless, systems of this kind have been used on a large scale in Soviet tanks, from the T-64 and T-72 onwards. In the case of the T-72 the magazine has taken the form of a carousel in which the rounds are stowed radially. This severely restricts the length of the rounds that can be stowed and requires therefore the use of separated, two-piece ammunition with projectiles and propellant charges held above each other in cassettes.

Restrictions on the length of the ammunition can be avoided to some extent by the use of a rectangular magazine in which the rounds are held parallel to each other at the bottom of the turret basket. Such a magazine was adopted for the original US automatic loading system which was tried in 1945 in a T22 medium tank (16.23). However the number of rounds that can be held in a rectangular magazine is smaller than in a carousel, which in the case of the T-72 contains 24 rounds, or in a vertical array.

To separate the ammunition from the crew without incurring the disadvantages

of it being in the turret bustle it has been proposed to locate it in the rear of the hull and to transfer it from there, one round at a time, to a turntable under the floor. The turntable would then align a round with the gun and a swinging arm would lift it for ramming into the breech. A system of this kind was designed by Rheinmetall for the proposed Swiss NKPz of 1979 but it was obviously complicated and the tank for which it was intended was never built.

A far simpler system with a swinging arm as an alternative to a hoist was built in 1985 for the prototype of the Close Combat Vehicle Light (CCVL), a light tank with a two-man turret mounting a 105mm gun which was developed in the United States by the FMC Corporation. In this case the ammunition was located on the left of the gun, where a human loader would normally stand, and the rounds, which were stowed vertically with the projectiles pointing upwards, were brought up to the loading arm by an endless chain conveyor. A somewhat similar system was also developed during the 1980s in Italy by OTO Melara for a one-man turret mounting a 60mm gun, which was intended for heavily armed infantry fighting vehicles.

Whatever its form, the adoption of automatic loading has been accompanied in general by a reduction of tank crews from four to three men. This has been opposed irrespective of the merits or demerits of the different loading systems on the grounds that, although the fourth crewman was no longer needed to load the gun, he was still wanted to help the other crewmen operate the tank for any length of time and to maintain it. The arguments in favour of retaining the fourth crewman have echoed those advanced earlier for retaining a five instead of four-man crew but this time they have been more convincing.

16.10 Turretless Tanks

In addition to being mounted on top of tank hulls in different types of turrets, or on pedestals, guns can also be mounted directly in the hulls. When this is done the resulting vehicles are known as turretless tanks, although this term could also be applied to tanks with guns mounted on pedestals. Moreover, in some cases guns have been mounted in hull superstructures which were, in effect, fixed turrets. But, even if some of them were not turretless in the very strict sense of the word, all the turretless tanks have had one major feature in common, namely very limited or even no traverse of their guns. Typically, the traverse has been limited to 10° or, at most, 15° to either side.

Because of the limited traverse of their guns, what would otherwise be known as turretless tanks have not been called tanks but assault guns, tank destroyers or self-propelled guns. This has been done on the grounds that vehicles whose guns have limited traverse can not be used like conventional, turreted tanks. However, the difference between turreted and turretless tank has been one of degree and not of principle and hardly justified the use of different designations. The real reason for it can be traced to the division between the artillery and the tank branches of armies, which resulted in turretless tanks having to be called something else when they were operated by the artillery as they usually were.

The practice of calling turretless tanks by other names has been followed in spite of the fact that the original British, French and German tanks of the First World War were all turretless. Moreover, it continued despite the use of turreted and turretless tanks alongside each other during the Second World War. Thus, units equipped with the turretless *Sturmgeschütz* formed for a time part of the tank regiments of the German Panzer divisions and in some Soviet tank brigades T-34

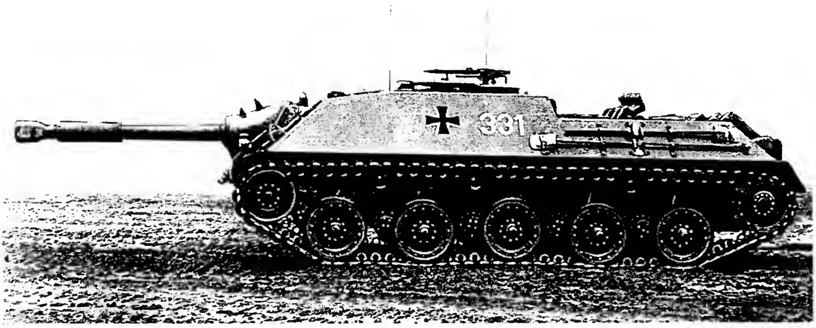


Fig. 16.17 German Jagdpanzer-Kanone *which followed the example of the turretless assault guns and tank destroyers of the Second World War.*

tanks were mixed with the turretless SU-85 right down to platoon level.

The only operational difference between turretless tanks and the others has been that they can not engage targets on the move unless these happen to be within a narrow frontal arc. In consequence they have been considered more suitable for use from stationary, defensive positions than for the mobile, offensive roles with which tanks are commonly associated. However, some of the turretless tanks have been designed specifically as assault vehicles, or in other words for an offensive role, albeit of a somewhat specialised nature.

Apart from restricting severely the arc over which turretless tanks can engage targets on the move, or from stationary positions unless they turn bodily, the mounting of their guns also increases the internal volume they need to have, to allow for the movement of the breech end of the guns not only in elevation, as in other tanks, but also in azimuth. On the other hand, the installation of guns in turretless tanks is not restricted by the diameter of the turret ring, which makes it possible to mount larger guns in them than in turreted tanks of the same size. This advantage was exploited many times during the Second World War when the need was perceived in Germany and in the Soviet Union to mount larger guns quickly in existing vehicles.

Like tanks with the driver in the turret, turretless tanks also enjoy the advantage of being able to dispense with the two-tier arrangement of the crew needed by conventional tanks. Most of them have in fact dispensed with this, which has reduced significantly their overall height. Thus, some of them, such as the JPz 4-5 produced in Germany during the mid-1960s, have been only 1.98m high to the top of their roofs.

But, in spite of their successful use during the Second World War, the advantages of turretless tanks have been outweighed since then by the disadvantages of the limited traverse of their guns. In consequence, only two more vehicles of the kind made popular by the introduction of the German *Sturmgeschütz* in 1940 have been produced in quantity since the Second World War. One of them has been the JPz 4-5 and the other its Soviet contemporary, the ASU-85.

However, there has been further interest in a different type of turretless tank exemplified by the S-tank developed in Sweden between 1958 and 1961 and

subsequently produced in quantity for the Swedish Army (16.24). In it the gun mounting has been fixed in relation to the hull, so that the gun can be elevated only by altering the pitch of the hull by means of an adjustable hydropneumatic suspension and it can only be traversed by turning the whole vehicle.

The idea of traversing the gun of a tank by turning the vehicle was originally incorporated in the SRB experimental tank designed in France in 1921 and was then adopted for the Char B which was produced for the French Army during the 1930s. For accuracy of traverse the SRB and after it the Char B relied on a double differential steering system with an infinitely variable hydrostatic drive, which was well in advance of other contemporary steering system. However, the method of aiming the 75mm gun of the Char B by turning it did not prove entirely successful and was abandoned in 1940 in its final version, the Char B1 ter. In this the gun was no longer fixed in traverse but could be traversed, independently of the hull, over an arc of 10°.

Nevertheless, twenty years later the S-tank proved that a gun could be aimed effectively by turning a vehicle with a steering system similar in principle to that of the Char B but more refined and operated by more sophisticated controls. In fact, the steering controls have been integrated with hull pitch and gun controls into a single unit, which makes the S-tank exceptionally easy to operate. The control unit is in the form of a box with handlebars and a number of buttons for loading and firing the armament of the tank: rotation of the box steers the vehicle while twisting of the handlebars alters the pitch of the hull. Both the driver/gunner and the commander of the S-tank, who are located on each side of the gun, are provided with such a control unit as well as accelerator and brake pedals, so that either can operate it by himself. This means that the S-tank can be operated in an emergency by one man, which is not possible with any other tank. Its normal crew consists of three men, the third man being seated behind the driver/gunner and facing rearwards. Apart from acting as a radio operator and watching over the rear sector, the third crewman is provided with a simplified set of driving controls so that he can drive the S-tank backwards, giving it a unique advantage in this respect over all other tanks.

Because its mounting is fixed, the gun of the S-tank is as close to the roof as in oscillating turrets, which means that less of its height needs to be exposed when firing from behind cover. For the same reason it has been possible, as in oscillating turrets, to provide the S-tank with a relatively simple automatic loading system. The latter feeds ammunition from a 50-round magazine located at the rear of the hull, where it is less vulnerable than elsewhere and where it can be easily and quickly reloaded from outside through two hatches in the rear hull plate. The installation of the magazine in the rear of the hull implies, of course, that the engine and transmission compartment of the S-tank is at the front, as already mentioned in the discussion of the relative merits of rear and front engine installations.

The one major disadvantage of the S-tank is that it is even less capable of engaging targets on the move than other turretless tanks. In fact, it can only do so if they happen to be straight ahead. But this disadvantage can be partially eliminated without sacrificing the principal advantages of its configuration by adopting a semi-fixed instead of the fixed gun mounting and by providing the gunner with an independently stabilised sight.

Semi-fixed guns, that is guns capable of movement in elevation in relation to the hull, were actually used in the French SRB and Char B. But they were not stabilised, which a semi-fixed gun needs to be if it is to be fired on the move. The

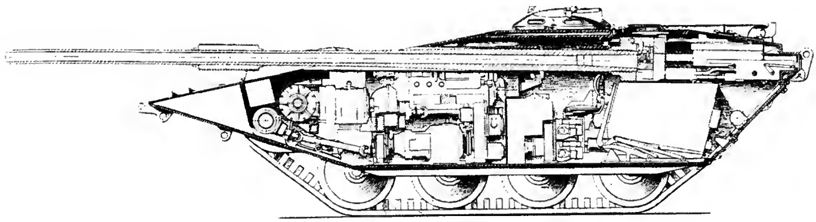


Fig. 16.18 Cross section of the turretless Swedish S-tank with a fixed gun mounting. (Bofors)

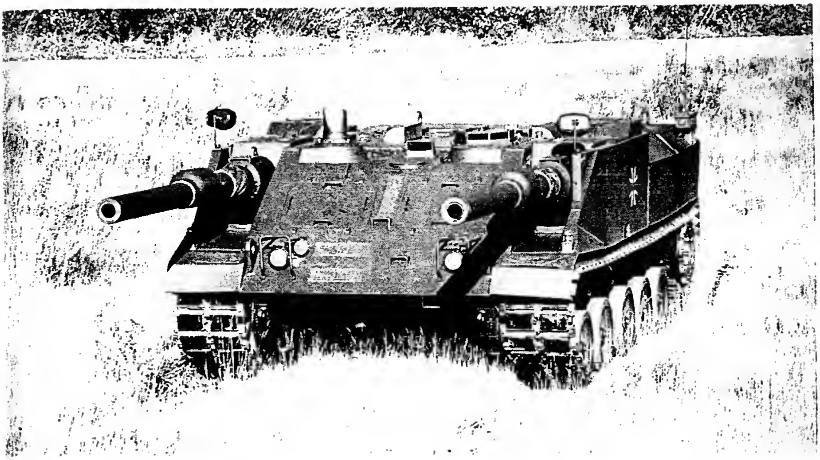


Fig. 16.19 German VT-1-2 experimental turretless tank with two 120mm guns in semi-fixed mountings. (Krupp MaK)

two French tanks also lacked an independently stabilised gunner's sight, which is essential for the acquisition of targets on the move and makes it possible to do this from a turretless tank as well as from any other. Hence, given a gun stabilised in elevation and an independently stabilised gunner's sight, all that remains for the turretless tank with a semi-fixed gun to do to engage targets on the move is to zig-zag or snake, instead of moving in a straight line. This makes its gun sweep over an arc and it can then fire on any target within that arc when in the course of its traverse the gun is in coincidence with the gunner's sight.

Such a procedure was adopted for the VT 1-1 and VT 1-2 experimental turretless tanks built in Germany in the early 1970s by Krupp MaK. Tests of them demonstrated that turretless tanks with semi-fixed guns could engage targets on the move as well as when they were stationary (16.25). But their design was highly questionable because they were armed not with one but with two 105mm or two 120mm guns. This enabled them to fire salvoes of two rounds and thereby increased their probability of hitting targets. But the installation of a second gun with its associated loading mechanism imposed considerable weight and space penalties and the firing of salvoes represented an inefficient approach to increasing hit

probability compared with firing bursts of two rounds from a single, automatically loaded gun. It is not surprising therefore that the development of the twin-gun turretless tanks did not advance beyond trials and was abandoned in 1976, although they had their advocates (16.26).

On the other hand turretless tanks with a single semi-fixed gun remain an attractive proposition. They do this because they represent the simplest type of tank and because they should, therefore, cost less to produce than others.

16.11 References

16.1 'The Automobile Club Show', *The Engineer*, Vol.87, 23 June 1899, pp.627-629.

16.2 R M Ogorkiewicz, 'Sixty Years of Armoured Car Development', *The Engineer*, Vol.208, No.5404, 21 August 1959, pp.98-101.

16.3 D Crow, ed., *British AFVs 1919-40*, Profile Publications, Windsor, 1970, pp.13-24.

16.4 B D Trott, J E Backofen and J J White, *Design Criteria for Ammunition Storage Compartments*, Proc. 2nd Symposium on Vulnerability and Survivability, Vol.1, American Defense Preparedness Assn., Washington, 1976, pp.65-89.

16.5 C L Pattie and R L Gray, *Development and Evaluation of a Semi-Reclining Driver's Seat for the XM-1 Tank*, SAE Paper 770250, Soc. Automotive Engineers, Warrendale, 1977.

16.6 Dubot, Barbaroux, Boussiron and Urvoy, 'L'AMX Leclerc', *Armement*, No.6, January 1987.

16.7 R E Jones, G H Rarey and R J Icks, *The Fighting Tanks since 1916*, National Service Publishing Co., Washington, 1933 pp.198-201.

16.8 P Touzin, *Les Vehicules Blindés Français 1945-1977*, Editions EPA, 1978, pp.52-63.

16.9 R P Hunnicutt, *Patton*, Presidio Press, Novato, 1984, pp.47-51.

16.10 R P Hunnicutt, *Firepower*, Presidio Press, Novato, 1988, pp.152-160.

16.11 *A History of Automatic Loading Equipment*, Report No.RR-13, Ordnance Tank Automotive Command, Centre Line, 1960, pp.86-91.

16.12 R P Hunnicutt, *Patton*, op.cit., pp.179-181.

16.13 W J Spielberger, *From Half-Track to Leopard 2*, Bernard & Graefe, Munich, 1979, pp.271-273.

16.14 *A History of Automatic Loading Equipment*, op.cit., pp.81-84.

16.15 E Drosen, Das Automatische Laden der Panzerkanone, *Soldat und Technik*, No.10, 1983, pp.540-545-

16.16 R P Hunnicutt, *Firepower*, op.cit., pp.112-113.

16.17 *Questionmark IV*, US Army Ordnance Tank-Automotive Command, August 1955, pp.3-10.

16.18 H de J Keays, Logical Methods in Tank Development, *British Army Journal*, July 1951, pp.27-33.

16.19 R M Ogorkiewicz, *Scorpion Reconnaissance Tank*, AFV/Weapons Profile No.34, Profile Publications, Windsor, 1971.

16.20 P Touzin, op.cit., pp.45-50.

16.21 *Handbook of Weaponry*, Rheinmetall GmbH, Düsseldorf, 1982, pp.406-408.

16.22 E Zielinsky, 'Considerations on Autoloaders for AFVs', *Military Technology*, No.2, 1987, pp.39-49.

16.23 *A History of Automatic Loading Equipment*, ibid., pp.5-13.

16.24 R M Ogorkiewicz, *S-Tank*, AFV/Weapons Profile No.128, Profile Publications, Windsor, 1971.

16.25 *H R Lembcke*, 'A Tank of the Future in the Context of German Defence Technology', *MaK Defense Journal*, No.5, November 1980, pp.20-24.

16.26 H Stark, *Panzer – Qualität oder Quantität*, Bernard & Graefe Munich, 1982.

Index

N